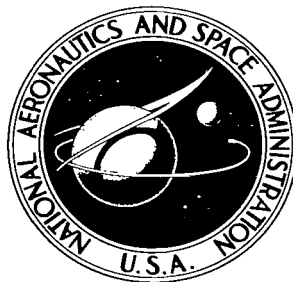
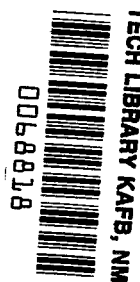


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COORDINATION OF MAN'S VOLUNTARY MOVEMENTS UNDER SPACE FLIGHT CONDITIONS

by L .V. Chkhaidze

Izdatel'stvo "Nauka", Moscow, 1965



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UNDER SPACE FLIGHT CONDITIONS

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Translation of "Koordinatsiya proizvol'nykh dvizheniy cheloveka
v usloviyakh kosmicheskogo poleta."
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COORDINATION OF MAN'S VOLUNTARY
MOVEMENTS UNDER SPACE FLIGHT CONDITIONS

L.V. Chkhaidze

ABSTRACT

The author presents the problems encountered in movement coordination of man in a changed gravitational field, such as will be experienced in space flights. Simulation of inertial forces occurring in accelerations, as well as flights of manned artificial earth satellites, made it possible to establish the experimental conditions for solving these problems.

The author believes that voluntary movements in man and higher animals may be regarded as a process consisting of two cycles: external, based on external afferentation, and internal - based on internal afferentation. Coordination of human voluntary movements is impaired when the gravitational field increases. The limits of the impairment depend on the state and training of the individual in this field. However, due to the properties of the central nervous system, reinforced by proper advance training, the coordination will return to a specific norm.

The human being's capacity to restore movement coordination by systematically performing a skill under overload conditions can form the future basis for the cosmonaut's physical training. The problem of movement coordination in a gravitational field which increases over a very long period of time requires further study.

FROM THE AUTHOR

The problem of coordination of movements in an altered gravitational field became apparent to researchers in its full scope and significance at the time of man's entry into the cosmos. /3*

The mechanisms, leading to the motor acts of living creatures which inhabit our planet, were formed under the constant action of the earth's specific gravitational field. Undoubtedly, the existence and size of the field had a decisive effect, during the course of thousands of years of evolution of man and animals, not only on the organization of the neural and muscular apparatuses, but, which is of no less importance, also on the organization of the entire activity of the central and peripheral mechanisms regulating the movements of the living organism.

During cosmic flight man must experience and endure many prolonged changes in the forces to which he is subjected - from accelerations at the start and during the trajectory of the spaceship's flight to complete weightlessness during the main part of the flight, and finally the possibility of encountering an unusual gravitational field at the landing site.

What will happen to man under these conditions? Will the coordination of his movements remain intact or, if it is disturbed, how and to what extent will it be affected? What measures should be taken in order that the cosmonaut may retain coordination in his vital and working skills? How should he be trained in order that he can re-establish the capability of correctly controlling his movements, if the danger of their disruption arises?

We have presented here a somewhat incomplete enumeration of the problems which arise, the solution of which is further complicated by the fact that the basic question--the principle of coordination of movements in man--has not been completely solved as yet, although an investigation has been conducted for a considerable length of time. In approaching these problems, we first had to systematize and generalize the most important material according to the general principles of coordination of voluntary movements of man and animals as a

* Note: Numbers in the margin indicate pagination in the original foreign text.

whole, to develop an applicable working hypothesis, and then on this basis to find ways for solving the questions raised.

The impossibility of creating a long-term state of complete weightlessness presented itself as an experimental difficulty in the research. The increase of the gravitational field was simulated by inertial forces occurring in accelerations, since from the physiological point of view the reproduction of the overload state occurring during accelerations is exactly identical to a rapid increase in gravity. A brief period of decreased weight was attained during airplane flights along a parabolic curve, and later for longer periods during flights of artificial earth satellites with cosmonauts on board. /4

As it will be evident from the content of the material which follows, this has made the solution of our problem possible. The hypothesis we adopted was successful enough to be taken as a basis for experiments which led to the conclusions that the coordination of man's movements under increased gravitation will be disturbed for a short period of time. However, due to the properties of the central nervous system, reinforced also by proper training, the coordination will return to a specific norm, if he will be able to withstand the resistance. In addition, both the possible disturbances as well as the course of the restoration were found to be subject to a specific dependence.

These conclusions were first extrapolated and later substantiated in practice during zero gravitation (in weightlessness), first of short duration and later of prolonged duration.

The above predetermines the order in which our material is presented. We shall begin with the description of general rules for the coordination of voluntary movements of man as a whole (including a number of generalities which we have formulated), and shall conclude with experimental proofs of the rules which are established, as well as with some practical recommendations directed toward the maintenance of coordination of movements in man during cosmic flight.

INTRODUCTION

The Soviet people were the first to realize one of the most daring dreams of mankind -- the mastering of cosmic space, and if anyone had any doubts of the strength and scope of our science, these doubts were buried after April 12, 1961. In the shortest possible time, precisely and decisively, the Soviet scientists solved an extensive group of problems relating to launching the spacecraft-satellites, and to preserving the viability of the cosmonaut and his return to Earth. No one is trying to depreciate the merits of the American scientists who, although considerably later, also solved these problems; nevertheless, the priority of Soviet science is completely indisputable. /5

The problem of placing spaceships into orbit can be divided basically into two categories -- technical and the medical-biological. If the solution of the first could in any way be accomplished through preliminary calculations, then the solution of the majority of the questions related to the viability of the cosmonaut in flight could be realized in no other way than experimentally, before man's actual entry into the cosmos.

From the whole complex of medical-biological problems, it was necessary to especially single out the question of coordination of voluntary movements of the cosmonaut in flight. We use this term to designate the capability of man to regulate his movements in such a way that he completely retains the working ability necessary for guiding the spaceship, and for maintaining the viability of his own organism.

It was within this narrow framework that we first raised this question. In reality, the problem was much broader.

Is it really possible to talk about the formation of motor skills, the combination of man's skills with those of a machine, and finally, about the methods and possibilities of "switching" on these skills during cosmic flight under conditions of great responsibility, which have never been previously experienced by man, if there is not enough physiological information on the motor skills in general and the mechanisms which cause its plasticity and ability to be switched on. /6

It must be honestly said that even in the first part of this century physiology still did not have the answers to both of these questions. The situation was further complicated by the fact that the minds of scientists, who were impatiently seeking the answers, readily substituted the actual reliable facts with unverified hypotheses. These were often worse than simple ignorance, because they

led scientific thought away from the correct course.

However, our native science during the recent years was able to clarify the problems of the physiology of movements, which had long remained unsolved, to a degree which was adequate for answering the physiological problems related to the Soviet cosmology at the time of its birth. However, even these answers and the practical conclusions which followed were possible only as a result of the immense revolutionary upheavals experienced during the last few years in the area of general physiology, and even biology as a whole.

It was these upheavals which for the first time created a stable scientific base for the most important problems of cosmonautics, which must be clarified briefly in this introduction. However, first we must mention the following.

No one can have any doubts, of course, that the magnitude of the earth's gravitational field, in the course of multi-millions of years of evolution of man and animals, had made its imprint on such purely physical phenomena as their movement in space, that is, on the voluntary movements of both the extremities and the body. Consequently, it was necessary first to solve the problem of whether the future cosmonaut would have the ability to preserve the coordinated regulation of habits earlier worked out on earth during the zero field. This solution was related to the activity of the fundamental central mechanisms regulating our vital functions and long adapted to the specific conditions of this regulation. This was the first step. Secondly, another question of no less importance immediately appeared -- what should be done, how should the astronaut be physically prepared so that this most important function could be re-established to some degree, if it were disturbed. Finally, it was just as important to determine the limits and other rules of these disturbances; otherwise, the solution to the second question would be impossible. It can be readily seen, that the solution of these problems is only possible through experimentation, and only with man, since we are talking about movements related to functions inherent to the higher nervous activity of man. To do this, however, it was necessary first of all to reproduce under laboratory conditions (or conditions close to them) the most important part of the future cosmic flight -- the zero gravitational field. How should /7 these experiments be arranged? How should the necessary observations be conducted if it is impossible to reproduce weightlessness for long periods which are necessary for the adaptation of physiological processes under conditions on earth? Consequently, new paths had to be found. The reader will be shown how they were found in the work by L. V. Chkhaidze, doctor of biological sciences. It is very important to state the following. Whatever approach was taken by the investigator, he first had to have a basic theory for the existing problem -- a knowledge of the methods and rules for man to control his extremities under normal conditions on earth. Only then could he solve the questions related to the disturbances of coordination of movements during changes in the gravitational field.

These problems are still not solved, and the author of this research had, first of all, to make a review of the theoretical area. Since the basic principles used by L. V. Chkhaidze in solving the problem were not only viable and helpful in reaching the established goals, but in our opinion, would be significant for solving other problems related to the coordination of man's movements, let us delve into them in more detail.

Having lived through a period of flourishing, an aging theory can be destroyed and become obsolete, first of all, when it contradicts the new inflow of facts and relationships which appear in experiments. Sometimes it is a gradual accumulation of facts which cannot fit the old theory, or one single fact or phenomenon which hits at the very heart of it that makes an immediate change necessary. At times, science must wait a long time for the moment when a penetrating genius appears on the battlefield, and is able to find and formulate a new, strong concept which destroys the previous ideas by its indisputable priority over them.

Such was the case with the unprincipled, complex, and obscure astronomic system of Ptolemaeus, which could not withstand the clear and convincing theory of Copernicus and Kepler. Two hundred years later the same happened to the phlogistron and thermogen theory: the discoveries of Lomonosov and Lavoisier - and later, the discovery of oxygen, which led to the correct understanding of the combustion process - quickly and indisputably revealed the whole absurdity of the phlogiston concepts, with overwhelming negative data. A similar irrevocable collapse of a theory was experienced at the start of this century by the Newton concept of absolute space and time which could not withstand the opposition of new experimental data; mainly, the brilliant laws of Einstein.

In other instances, the change in the scientific theories is /8 not quite as radical as in the historical examples cited above. In those instances, the supplanting of the old theory does not occur because an inaccuracy or an irregularity was discovered. The new concept, which supersedes the old one, takes precedence over it either because it has the capacity to encompass and generalize a much greater series of phenomena than before with one formulation, or because it has a much greater heuristic force. A vivid example of such a generalized theory is the electromagnetic field theory, originated by Maxwell and based on the generalization of facts discovered by Faraday and Oersted. The emergence of this theory, composed of brilliant equations by Maxwell, made it possible to encompass with a single formulation, areas of physics which until then were treated as completely different divisions. Maxwell's theory was able to survey, at one time, as if from a bird's eye-view, the science of light, the theory of radiant heat, and electromagnetic induction - it led directly towards the prediction of waves, which was discovered by Hertz and became the basis of radio engineering.

An example of no less distinction than the ones mentioned above,

was the creation of the kinetic theory of gases and solutions, which did not actually disprove anything or detect any errors. However, it opened up broad pathways which led to the discovery of new regularities never previously imagined. The crisis, which biology and all of the related natural sciences are undergoing now, clearly belongs to this category of revision and extension of old concepts. The most distinct feature of this process is the richness of generalizations, which continually grows before our very eyes and which leads the researcher directly toward new experiments and investigations. Along with this, the same critical process gives birth to new concepts, terms, and formulations which serve science in the role of stronger, more perfect, and more precise weapons of scientific progress. The first place among these weapons is occupied by that aggregate of theoretical and applied investigations, which are combined under the term of cybernetics.

Each science outgrows the stage of pure empiricism, and becomes a science in the full sense of the word at that moment when it is capable of applying two specific questions to each phenomenon within the particular field: (1) How does the phenomenon originate, and (2) why does it originate? The first question stimulates the search for qualitative descriptions, and then for the quantitative characteristics. The second question demands that all of the decisions about these phenomena be founded on the grounds of strict causality, and it leads toward the formulation of laws governing the course and the dependence of these phenomena - which are first qualitatively described and which are later formulated in strict mathematical models of established causal dependence. /9

It is adequate to trace only the history of the origin and development of any science in non-living nature to become convinced of the accuracy of these statements. In some sciences, these moments of change-over - in the search for an accurate description of phenomena (how?), followed by a clarification of their causes and relations (why?) - came sooner - in others, later - but in our time there is no single science of non-living nature which does not possess in full measure both of the cardinal questions within its methodology.

The biological sciences, physiology, pathology, psychology, and genetics, have employed their strongest workers and methodologists in an attempt to subordinate the phenomena of areas they investigated to the same two cardinal questions. In following the line of the question "how", in spite of the complexity and difficulty entailed in an accurate quantitative description of vital phenomena, the techniques of observation and the perfection of measurement apparatus steadily progressed. In the causality line of investigation, although difficulties had to be overcome which were much greater than in the sciences of non-living nature, the fund of information - which conclusively revealed the causal connections between phenomena and even allowed (although not too often) quantitative, mathematical formulations - became enriched.

But more and more, one very remarkable feature became apparent in biological science. In physics, in chemistry, in astronomy - wherever it was possible to find and express the law of causality for these and other phenomena - this law became definite, without reservations, and for the given stage of knowledge -- exhaustive and strict. In biology, however, in each attempt to formulate a law for the phenomena, it either was impossible to translate such a law into a strictly mathematical form, or it was impossible not to feel that something very essential and even decisive was missing. Often attempts were made to explain this "slipperiness" of biological formulations by the immense complexity of the question and the abundance of variables it contained, but it was impossible not to notice that the matter was deeper and more fundamental. That which, according to all evidence, seemed to be a law (in physiology, psychology, etc.), as a rule, had absolutely no element of prediction, and for that reason, sooner or later, without exception led to a theoretical dead-end. The criterion given by Lenin of checking through trial - the severest criterion for the suitability of a concept laying claim to being a law - in a large percentage of cases led to the conclusion that something was wrong with this law.

Numerous observations and facts in various problems of biology indicated to the scientists, even during the last century, the indisputable expediency of mechanisms and systems inherent to living organisms. This expediency became immediately evident as a distinct, and perhaps even decisive, characteristic of living systems, separating them from any other phenomena of non-living nature. Inevitably, the question always arose: "for what?" does this or that apparatus exist and serve the organism. Also, in which direction is it headed? What problem, easily accessible to observation, is it destined to solve? To a still greater degree, the idea crystallized that - not why the biologist is plagued by failure or dissatisfaction in his attempt to solve this or another question - but that, as applied to biological problems, it is necessary - in addition to the two questions of "how" and "why", which are adequate for physics and chemistry - to ask a third question, "for what?". /10

This conclusion was appalling to the mechanical materialists of the 19th century. Was it possible to presume that the purpose of action -- that which must be accomplished and can become a reality only in the future -- could be the cause of this action? The cause follows its result! Only idealistic finalism (it seemed) could accept and adopt such an anti-materialistic structure.

In some cases, by means of truly brilliant thought, it was possible to completely substantiate and explain the appropriateness of vital phenomena, without going beyond the limits of the questions of "how" and "why". This, for example, was done by Darwin in his concepts of the struggle for life and the survival of the fittest. It is true that here, without going beyond the limits of the strictest law of causality, it was possible to indicate how purely the accidental phenomena of

genetically-transmitted mutations could be screened, and changed into expedient adaptations of organisms and decisive factors of evolution. However, we cannot omit the fact that, first of all, among the vast circle of the problems of biology, syntheses similar to Darwin's are more likely to be infrequent exceptions than they are to be the general rule. Secondly, in Darwin's system itself, the further one delved the more frequent were the "blank spots", consisting of incompletely solved questions, obscurities, and plain inexplicabilities.

In the meantime, the presence not only of the statistical expediency, but also of dynamic and active purposefulness in all areas related to the science of biology was becoming completely indisputable. The initial results of a cybernetic investigation of control, regulation, and connection immediately marked a deep parallelism between the artificial systems of self-regulation and the apparatuses observed in living creatures. However, apparatuses of this type are created by man with a specific purpose of, so to speak, enriching the possibilities of man's organism itself, by using these apparatuses as a super-structure of stronger, and more effective organs of man. The course toward attaining the goal, by means of each of these structures, is effected and coded in the form of a basic program of functioning. A very close, formally organized, and objective analogy - between these purposely-created systems and the systems of control and regulation in organisms - directs our thought toward the recognition in the organisms and systems of a definite and decisive purposeful direction, and along with this, complete legitimacy of the question, "for what?", as related to these systems. However, the parallels, discovered and investigated by cybernetics, made it possible to by-pass the methodological difficulty which seemed insurmountable to the mechanically-orientated materialists of the last century. /11

The purpose, which lies in the future, cannot in itself be the cause of the phenomena and actions taking place at the present time. This is clear to us, to the same degree as it was for our predecessors a hundred years ago. But we now know that such a problem or goal, contemplated and planned for the future, can be coded and included into the "memory" of the structure in the form of its model, and can really exist at the present time. This coded "model of the future" (as I called it in one of my previous works) and the program of action directed toward the solution of the given problem and toward attaining the purpose, occurs earlier than the action which they both stipulate. The law of causality in this manner does not suffer any loss, and the idea of expediency and purposeful direction of organisms, which distinguish decisively the latter from the phenomena of non-living nature, can firmly rest on the foundation of dialectical materialism. This is what our predecessors-biologists did not and could not know.

However, the most important trait of all of the living systems, functioning on the basis of the three questions which were described above (that is, including the question, "for what?") became apparent

later than others, in spite of the fact that it is possibly the most important and determining characteristic. This trait should be called an activity (physiological and biological).

How is purposeful direction characterized to the greatest degree? The organism is always interacting with the external and internal environment. If its motion (in the general sense of the word) has the same direction as the motion of the environment, this is accomplished smoothly and without conflict. But if the programmed movement toward the specific goal demands overcoming the environment, the organism releases a great deal of negative entropy for this purpose, until this organism either triumphs over the environment or perishes. The medium, as is thermodynamically intrinsic to all non-living aggregates, moves always in the direction of entropy growth. An organism, in its ontogenic development and formation and in its activity according to the pattern of life, moves, as a rule, anti-entropically, striving for a sharp decrease of entropy in itself and in the surroundings it is trying to overcome. Naturally, such a result is attained due to the fact that the organism as an open system purchases this effect of negative entropy at the price of a metabolic rise in the entropy of the metabolism products which are oxidized and destroyed by it. It develops these products outside. /12

Now it is quite clear to us why the biologists, who limited themselves to answering "how?" and "why?", always met with failure. Here we could bring out many good examples. I shall limit myself to one, since it is closer to the theme of this introduction and to the entire monograph of Dr. L. V. Chkhaidze. This is the example of the reflex theory.

The reflex theory (according to the arch scheme) made it possible to examine this mechanism as a basic brick which, when added to a group of others, possibly produces a complete theory of behavior. This assertion was especially strengthened after Pavlov's discovery of the phenomenon of conditioned closures - that is, a very flexible shifting of the reflex arches of the unconditioned reflexes. The reflex, according to the scheme of the arch, is, in the strictest sense, a model of the law of causality: the excitation and its pathway along the afferent semi-arch being the cause; the reaction and the course of its travel along the effector neurons being its definite effect. It followed from this that, first of all, the entire reorganization of the acquired reflexes, all of which are conditioned closures accumulated in the course of life, are completely determined by those actions of the environment which are communicated to the brain along the afferent semi-arch. That is, the organism actually follows the lead of the environment and its influences. Secondly, this gave rise to the formulation widely used by I. P. Pavlov: life is an interaction of the organism and the environment and, in addition, a balance with the environment. The indisputable fact that through motion, the organism does not just interact with the environment, but actively acts upon it, striving to change it to serve its needs - and that the

science of vital dynamics is only possible when there is an apparent under-balanced remainder - all of this opposes these previous formulations. It is not the equilibrium with the environment and not the balancing with it that determines the vital activity and the behavior /13 of each organism, but it is the model of the future which is necessary to it that is the motive power of any organism. The organism, in obeying it, we might say, does not pay any attention to whether it has to move with the tide, or against the tide toward the goal. It moves all of its life in spite of any "tide" in the environment which acts upon it.

A very characteristic gap in the reflex theory - which is simply caused by not taking into account the question "for what?" - is the difficulty of treating the most important function of generalization within its framework. When a new reflex is developed in an animal by means of repeated application of a conditioned stimulus with an appropriate reinforcement, as we know it, during the first phase of its formation, irradiation takes place - that is, the inability of the nervous system to recognize an entire wide group of similar stimuli. It can be readily seen that such irradiation has nothing in common with the generalization phenomenon, if only because the irradiation is quickly overcome during the subsequent phase of reflex development and is superseded by concentration, which alone explains the very sensitive differentiations which later take place. In this manner, irradiation stands before us in this process as a definite, negative phenomenon, which can be best compared to a photograph which is blurry due to poor focus. In contrast, generalization is a clearly positive complex of mechanisms, which is essential to the individual. Strictly speaking, no acquired (conditioned) reflex, in its finest differentiation, by itself enriches the vital experience of the species. It remains somewhat episodic and is not included in any classification until the process of generalization begins to function. This process is always active. Its classifying function is possible in no other way than in the presence of directives necessary for classification, and the derivation of these directives can be explained only by following the line of questioning, "for what?". Any number of elements, generally speaking, can be systematized and reclassified in numerous ways. What causes the fact that the organism each time selects one specific scheme for controlling the majority of actions in the environment, if it does not base this selection on purposeful significance - that is, on the category of "for what?".

P. K. Anokhin described, under the title of "acceptor of action", the mechanism undoubtedly related to this group of central nervous mechanisms. The goal of the acceptor, according to Anokhin, is to determine the moment when the required result of action is attained, and to command the subordinate apparatuses to stop. However, evidently the information transmitted to such an acceptor, from the periphery /14 of the functioning organs and from the objects of their action, must be for the purpose of triggering this acceptor mechanism, compared with internal information which was processed previously. It can

be readily seen that the source of this latter process can only be the "model of the necessary future", of which we spoke earlier.

Along with this, the comparatively highly-organized animals are worthy of mention (and, in the same manner, plants), in which this coded model of the future undoubtedly becomes more complex. Depending on the situation, two model forms can be distinguished. In other works, I designated these two co-existing models as: (1)-the model of the necessary future, and (2)-the model of the possible (prognosticated) future. Only at the lowest stages of development (unicellular organisms, lowest worms, etc.) does the organism "know" what it needs, but it moves in the direction of its necessary future, so to speak, head on, on the basis of the most primitive orientation. The higher organisms manifest their activity, based on the probable prognosis of where the current changes in the environment are heading, and on the prognosis of what sudden (highly informative) phenomena must be considered a priori with certain probability. Along with animals, these indisputable prognostic mechanisms exist in plants, and it is not purely by accident that an experienced agronomist or a ranger reaches a conclusion about future changes in the meteosphere on the basis of advance reactions in some types of plants: the folding of leaves, closing of flower sepals, wilting or straightening of the stem, etc.

The method by which the motor act is controlled, which was proposed by L. V. Chkhaidze and which is substantiated in detail in the first part of this book, deserves serious attention because of essential characteristics of this control, which were first noticed and pointed out by him. All the statements given above about physiological activity and modeling of the future are necessary to provide a valid description of the valuable material which is covered by this scheme.

I shall mention here now that, to a certain degree, one vulnerable spot in the method of Chkhaidze is the unnecessarily schematized, clear distinction, not only between the primary information currents from the exteroceptors and the proprioceptors, but also between their subsequent tracerebral routes, including the closure of the corresponding reflex sections. Such a distinction is not justified, first of all, because the primary afferent currents, even in the lowest cellular nuclei of the brain, are reorganized in a most effective manner (for the visual function, for example, this type of a deep change takes place even in the neural cells of the eye retina itself). Extensively and /15 actively-organized sensory syntheses - in which signals from all possible types of peripheral receptors, which are processed in the lower nuclei, grow together beyond recognition - even reach the central apparatuses, which fulfill the actual functions of control and coordination. Of course, this is not the core of the matter, and a more precise definition of the method in this respect does not signify a principal change and does not affect the essential elements presented by this method. The essential matter is as follows.

The alternate model of the necessary future, which determines the

initiative and the start of the action in response to it, directs the most important thought pattern of this action. In one of my works, I compared this process of planning action to a unique type of interpolation - to determine those sequential stages or points of action which are necessary for attaining the necessary result. But a very important characteristic of such planning interpolation is always its generalization. The control center which marks (or, according to Chkhaidze, "assigns") the plan of action and its thought structure, and partly its motor composition, never approaches literal detailedness of motor act elements. It can be stated that the control center's production is not one or another single function, but an entire package or family of functions, which are united and generalized according to some principle. This principle, we must note, is always selected in the final analysis as a possible answer to the same question, "for what?".

A more specific definition of such generalized order, the selection of a specific solution (depending on the circumstances), and finally the process of the constant coordinative collation of the current afferent signalization with the demands of the program -- all of this is attained by a portion of a subordinate division (or, it may be a whole series of divisions) which controls and corrects the motion - making sure that it is correct and suitable.

The value of the method proposed by L. V. Chkhaidze consists in the precise demarcation of both command apparatuses, along with a designation of the subordination relations between them. It can be stated figuratively that the new and the valuable material is contained in the upper half of the method examined, which does not lose importance for those corrections which the lower part demands. (See Figure 7.)

The most important fact of the generalization of the supreme commands, which are determined as a result of active modeling action, can be proven and reinforced by a very wide group of observations. First of all, it is necessary to recall the phenomena of switching and /16 reorganization within the nervous system. As we know, the reflex concept - when it comes to the questions which deal with generalization of thought - is completely powerless. An almost passive accumulation of single elements of living experience, which can only ensue from conditional closures accidentally acquired here and there, can, at the most, clarify some form of interpolation between those elements for us. But that necessary extrapolation, which is indispensable for any conclusion reached by induction, cannot be explained by the reflex concept.

Nevertheless, the experiments indicate that the living creature, having found itself for the first time in its life under conditions it has never before experienced - conditions which were never experienced by its ancestors - very quickly (often immediately) reorganizes to the full extent that is necessary for operating under these conditions, no matter how unusual or monstrous they are. If we examine or just scan through the wide list of experiments conducted on various species of animals, both vertebrates and arthropodae, which resulted in mutilation

of their locomotive organs (experiments of Bete, Gol'dshteyn, Trendelenburg, Asratyan, Anokhin and others), we shall see that in all of these experiments one characteristic is evident, which is common to all of the observed results. Coordination reorganization, which is indispensable for re-establishing locomotion, ensues in the animal subjects either immediately (immediately after the trauma in insects, or after the healing of the surgical wound in mammals) or - in all other cases without exception - much faster than any laboratory-conditioned reflex can be developed in the same species of animals under laboratory conditions. Bete, in experiments with beetles, amputated one, two, or even three extremities at a time, out of six. Each time, in place of the inherent program of rhythmic alternation of the extremities in walking, instantly - without preparation or practice - a new program, which by necessity differed from the natural one, appeared on the scene. This program was fully coordinated and suitable for locomotion. Of course, it would be absurd to propose that in this type of an insect (and, consequently, in all members of this species, since any of them could have been the object of the amputation experiment) from the very beginning, from the moment of birth, the coordination programs for all possible variations of such amputations are embedded somewhere in the lasting memory. This could not be explained by any theory of evolutionary adaptation.

In experiments with dogs and cats (Asratyan, Anokhin and co-workers) - both in amputations and experimental chiasm of flexor tendons and the extensor in one of the extremities - the reorganization to confident locomotion did not take place at once (which can be explained, evidently, by the more complex conditions of coordinative movements in vertebrate animals, as compared to the arthropodae). However, in all cases and /17 under all experimental variations, the reorganization was accomplished considerably faster than the development of any salivary conditioned reflex in the same animals. Evidently, in every scheme, for the number of individuals striving to explain all behavior phenomena by means of conditioned closures the situation should really be reversed: a synthesis or structure, or a chain of conditioned reflexes, could never be formed, on the whole, faster than each newly-formed conditioned reflex which constitutes it separately. This means that the explanation is not found here.

I shall mention here in only a few words some facts which were analyzed in my other works in greater detail, facts which are certainly less traumatic, but not less convincing. If a man writes once on paper with a pen, the next time with chalk, on a vertical classboard, one time -- in small writing, the other in large writing, etc. -- he accomplishes this process by means of a different chain of kinematics and a different selection of muscles in each case. However, in all of these cases the form of his writing is accurately retained, which leaves no doubt as to the fact that this writing belongs to the particular individual. But, in addition, if the man is subjected to some sort of a model amputation - such as the attachment of a pencil to his wrist or elbow, or if he is asked to hold the pencil in his teeth, as if he had lost his arm - even then with all these experimental variations, including the most unusual ones, such as writing with the toe of the left foot, etc., the writing inherent to the particular individual is immediately apparent without

any preliminary training. The letters are angular, and the lines are unsteady, but the essential characteristics of the writing and his individual character, are clearly evident.

The extent to which these last, strictly external coordination defects can be eradicated after training, is shown by the samples from my collection of letters of armless invalids. In these samples, the letters written by hand prosthesis, the writing performed with a pencil held between the teeth, and a letter written with the toe of the right foot can hardly be distinguished one from the other.

All the examples which are mentioned and examined above, with the complete mutual agreement of the results ensuing from them, indicate one capital fact: the immense and expedient generalization of those commands which are given to the subordinate apparatuses for concrete coordinative control of movement or action by the superior control section. It is not the elements (reflexes) that are the primary source from which unsuccessful attempts are made to formulate the generalized command in the form of a secondary result. The situation, according to all information, is exactly the reverse, and any detailed analysis of the motor act program must be examined as a specific /18 result of the widely-generalized and suitably well-ordered command matrix of control, which gives rise to it.

The idea that the higher control centers perform their function by triggering the lower apparatuses (in this case - the cerebrospinal) - which is their form of the command matrix, which makes it possible for these centers to adapt - was very recently mentioned and put into mathematical form by I. M. Gelfand, V. S. Gurfinkel', and M. L. Tsetlin. The ideas of these authors, aside from their complete accord with the statements given above, are interesting and heuristically fruitful, due to the fact that the processes which take place in the lower apparatuses, within the framework of the matrices given to them, are carried out, in their opinion, in a close, formal analogy with the processes studied by the game theory. In the same way that the theory of probabilities, which originated two centuries ago, was at first thought to be material for gambling and other amusements, but later became a powerful tool in the study of many physical phenomena, the same thing occurred with the mathematical theory of games, in our opinion. Greatly surpassing its original goal, which is indicated by its title, this theory has at the present time become one of the most valuable tools of cybernetic analysis. For obvious reasons, it is especially valuable for the problems of physiology and biology of activity. The problems of the game theory involve all questions of struggle, of conflict with the environment, the active conquest of the environment, etc. In this manner, we can see that the problems of activity are more and more becoming a part of physiological analysis, of the questions of coordination, behavior, central control, etc.

The experimental part of this book by L. V. Chkhaidze is definitely related to the problems of switching and central reorganizations, which

we discussed in the last few paragraphs of this introduction. However, in addition it is of special interest, in that it subjects the motor coordination of man to experimentation under conditions which are completely unique and which have never before been experienced by the subjects investigated or by their ancestors in the entire phylogenesis. The fact, which is directly substantiated by the present study, that - in spite of the extraordinary conditions surrounding the subject of these experiments - coordination is established and regulated quickly and precisely, is directly explained by the general considerations which were formulated above. On a practical, applied plane, this fact indicates that the coordination reorganizations, which are related to the presence of man in sharply-altered, gravitational conditions, will undoubtedly play a large part in his program of adaptation to cosmic flight under close conditions. Theoretically speaking,^{/19} it is justifiable to examine the thoughtfully and carefully-conducted study of L. V. Chkhaidze as a valuable and convincing contribution to the theory of motor coordination and control of the motor acts. Naturally, only the very first steps have been taken so far, but not only this study, but also cosmonautics itself, is just a few years old. In the future, more extensive, experimental investigations and more precise mathematical models of the discussed area will soon considerably enrich our theoretical ideas on physiology and the biomechanical activity. They will serve the future growing generation of daring heroes of cosmonautics as a valuable support in their preparation for further cosmic flights.

N. A. Bernshteyn

CHAPTER I

GENERAL PRINCIPLES OF COORDINATION IN VOLUNTARY MOVEMENTS OF MAN

This chapter is devoted to examining the question of coordination /20 in the voluntary movements of man from the theoretical point of view, which would make it possible to establish a number of general rules which are necessary for further analysis of the explicit motor act.

We are thus proceeding from the fact that the motor act of man (and higher animals) is a very complex process, the biomechanical structure of which can never be excluded from an examination of its coordination. A study of the quantitative interaction of the organism with the general force field of motion immediately indicates that it would be completely impermissible to limit the investigation to just the physiological side of the problem. It is also necessary to deal with biomechanical conditions.

We have felt it was possible to select general rules for the control of regulating systems which would permit the examination of the problem from the requisite view points. The extent to which this attempt is successful will be indicated in the following material. In any case, this will make it possible to present the depth and scope of this problem in its entirety, developing the positions presented earlier by the author (Chkhaidze, 1960, 1962). Simultaneously, it must serve as a foundation for solving the questions constituting the described investigations.

We will make the reservation that only those motor acts which - in addition to the obvious explicit synergic part - also contain the mental solution of a specific motor problem will be investigated.

We shall call these movements voluntary (although this term is somewhat inadequate).

We find it necessary also to preface our theoretical ideas with a short history of the development of research on the coordination of voluntary movements in man.

The beginning of research on the biomechanical aspect of /21 coordination of voluntary movements in man was initiated by the Weber brothers (W. and W. Weber, 1836), who conducted the first, most primitive analysis of walking. It should be mentioned that a number of pronouncements on the biomechanics of animal motion were made by Leonardo de Vinci, and the first observations of the location of the center of gravity in man -- by Borelli (Borelli, 1679). Later, the locomotion of man was studied by Meyer (V. Meyer, 1853), Marey (Marey, 1871), and Muybridge (Muybridge, 1891). However, all of these investigations never went beyond the framework of an investigation of the exterior side of motion, and did not touch upon their coordinating

structure, although the last two investigators applied the cinematography method.

The first step in the direction of a detailed study of the biomechanics of motion was not made until the end of XIX century by the German scientists Braune and Fischer (W. Braune and O. Fischer, 1895 -- 1904) who, having perfected the method of recording movements, studied in detail the dynamic side of extremity displacements and the general center of gravity in man during normal walking. The inadequacy of Braune's and Fischer's research was that, having compiled an immense number of calculations, they hardly ever utilized them in the future, therefore bypassing the most important fluctuations in the forces applied to the extremities. They omitted from their observations the most valuable one - the effect of the operation of the central apparatuses, which control man's walking, on the muscular periphery.

After World War I, the biomechanics of motion was investigated by "geilorists". However, their investigations (Amar, Gilbret, Townsend and others) were conducted within most narrow practical frameworks of finding methods and ways of increasing labor production, without any attempts to penetrate into the coordinative essence of man's movements. The methodology of these investigations was a step backwards, as compared to the methods of Braune and Fischer.

An extensive investigation of the coordination of man's movements is being conducted in the Soviet Union. The goal of this investigation is a detailed study of the entire biomechanical picture of coordinating structure of voluntary movements in man, for the purpose of establishing general rules determining both the central control and the operation of the muscular periphery of this most important vital process. This is necessary for discovering scientific methods of facilitating labor production, other higher accomplishments of man (for example, sports), and methods for use in medical practice.

K. Kh. Kekcheyeo (1923), who used the method of Braune and Fischer, with certain improvements, for investigating pathological gaits, should be considered a pioneer in this area of Soviet research.

An important, if not decisive, qualitative leap in the extensive /22 analysis of the coordinative structure of man's movements was accomplished by N. A. Bernshteyn who, during the period from 1923 to 1949, investigated many forms of motor acts, under normal conditions as well as during maximum neuromuscular stress.

Together with N. A. Bernshteyn during the same period, a large group of researchers studied a number of other movements which have an important bearing on the manifestations of vital functions of man (Popova, Shpillberg, Zal'tsgeber, Chkhaidze, Osipov, Sadchikov, Sheves, Ukran, Donskoi, Sorokin, Kotel'nikova, Semenov, Butovich, Alikhanov, Nepomnyashchiy, Subbotina, Yananis, and others). At the end of the forties, a great deal of research was conducted on biomechanical movements of human limbs under prosthesis (Gurfinkel, Slavutskiy,

Balakhovskiy, Fridman, Komendantov, Malkin, and others).

All of these investigations were conducted mainly by the cyclographic method developed by N. A. Bernshteyn. This method made it possible to calculate as much data in one week as it took Braune and Fischer to calculate in half a year. A. A. Ukhtomskiy (1927) gave this method a very high evaluation: "No other method of recording the motor reactions of an organism is as complete and objective as the cyclogramometric method. No single previous method for studying the motor reactions has such clear representation and accuracy as the method of cyclogrametry."

As a result of all of those experiments, at the end of the forties a great deal of experimental material had accumulated in the hands of the researchers. This material indicated that any motor act of man is an extremely complex process, a simple explanation of which, without considering the entire dynamic structure, would be untenable.

Indeed, if we trace just the growth genesis for the biomechanics of elementary walking (Popova, 1940), the changes in the structure of running under the influence of training (Bernshteyn, 1940), (Chkhaidze, 1958) or fatigue (Chkhaidze, 1948), it can be readily shown that the fundamental dynamic components of these movements evolve in a complex manner and are subject to specific rules, both in their development and degeneration.

Simultaneously, it was shown (Bernshteyn, 1935) that the biomechanics of any motion is first of all a result of quantitative interaction between the organism and the general field of force for the motion. This leads, finally, to the concept that the true interrelation between muscular strength and the resulting motion (which is necessary for accomplishing the coordinated motor act) requires a continual introduction of adjusting signals into the operation of the entire muscular periphery. The signals themselves represent a central response to everything that takes place in the periphery. Such was the principle for the sensory adjustment of movements in human extremities, which was advanced as far back as the end of the last century by I. M. Sechenov.

Meanwhile, strides in modern physiology made it possible to reach a more or less clear idea of the operation of - if not all, in any case the most important - divisions of the central nervous system.

Thus, it became possible to unify physiological data with the biomechanical research. This unification, which was started as far back as the thirties (Bernshteyn, 1935), led to the development of a theory of motion coordination levels, the basic ideas of which greatly determined the pronouncements of cyberneticians on the principles for controlling movements in a living organism.

It is a pity that the progressiveness of these views was not immediately accepted. The basic work of N. A. Bernshteyn, "On the

Structure of Movements" (1947), was subjected to criticism, which now could hardly be considered valid. Only later, when the vitality and validity of these pronouncements was clear, did they gradually earn their rightful place.

This coincided with further improvement in the investigation methods. Tensometry, which made it possible to obtain, within a few minutes, the data which took weeks to obtain before, was developed. Such a methodology made it possible to collect masses of material, and in so doing removed the most important shortcomings of biomechanical investigations.

Thus, a new era ensued in the development of biomechanics as a science. Subsequent works of N. A. Bernshteyn (1961, 1962), I. M. Gel'fand, V. S. Gurfinkel and M. L. Tseytlin (1962) and L. V. Chkhaidze (1962) summarized several theoretical pronouncements, while the resolution of some practical questions - related, for example, to prothesis (Gurfinkel' and Sysin, 1956) or to athletic training (Chkhaidze, 1948-1962, Hochmuth and Marchold, 1956 and others) - proved its competence as an independent discipline.

Finally, the theory and the methods of biomechanics⁽¹⁾ are being employed in the solution of important problems of modern science. The practical solution of one of these problems is presented in this work.

THE FUNDAMENTAL BIOPHYSICAL (BIOMECHANICAL) CHARACTERISTICS OF VOLUNTARY MOVEMENT CONTROL

Let us examine from the biophysical (biomechanical) point of view /24 the problems confronting the central nervous system in the control of voluntary movements. We are using the term problem to designate those physical rules which determine the course followed in completing a given movement, and which must naturally be considered in investigating the operation of the central apparatuses controlling motion. There are many factors which we mentioned above, but we shall deal only with those which play a decisive role in the control of motion.

The Concept of the External and Internal Forces

Any external forces can act on a human organism as well as on any other physical body. One of these forces is in constant operation --

(1) We employ this term to designate an entire complex of questions related to coordination of movements of living creatures, from the physical aspect of movements which take place along the osteo-muscular periphery, to the operation of the central apparatuses controlling these movements. We also consider it to be one of the divisions of biophysics.

this is the force of gravity. In the course of evolution, beginning from the very first steps of development, this force and its magnitude played a decisive role, not only during the formation of the hard, supporting skeleton and the muscles of a living creature, but also in the ontogenesis of the so-called "muscular sensation", that is, the activity of proprioception. Actually, as will be seen in the statements below, the completion of any motor act is impossible without a clear, to the most specific detail, and complete representation of the position of all sections of the body in space, and of the forces which act upon them.

The formations which provide signals as to the positions of the body sections are the muscular receptors, determining the amount of the muscular strength; the tendinous receptors, determining the amount of tendon tension, that is, the actual size of the angle of the joint, and finally, the articular receptors, which act together with the tendinous receptors.

Without going into a detailed anatomical-physiological description of the structure and the function of these organs, we would like to remark that the accumulation of signals for subsequent transmission to the central nervous system is based on the tension of those muscles and tendons to which they are connected. This gives us the right to call them mechanoreceptors.

Naturally, since the constant force acting on the limbs is the force of gravity, it plays a decisive role, not only in the formation of these receptors, but, which is more important, in the synthesis and processing of information which is transmitted from them to the central nervous system.

All of the other stresses applied from without, capable of accelerating the entire body or its sections, regardless of the signal, size, or direction, also belong to the external forces.

Muscular tension is the internal physical force of the human body. Acting on the separate sections⁽¹⁾, it produces some motion. In its interaction with the fulcrum, this force makes it possible for a man to move. However, one very important, from the physical point of view, characteristic in the structure and the function of the muscular apparatus of the human body should be noted. Almost all the muscles act on the hard parts of the body sections as on levers. However, almost always the muscles act on the smaller arm of the lever (Figure 1). As a result, in a muscle motion, which is comparatively small with respect to extension, the section or the extremity describes a much greater trajectory. It can be readily seen that this characteristic in the structure of the osteomuscular ganglions must

/25

(1) The term section used here and later on, designates the separate anatomical unit (bone) which has an independent mobility.

evoke additional complexities in the central control of motion, since an increase in the section motion trajectory is connected to many mobility degrees of freedom which are inherent to the human body as to a kinematic chain.

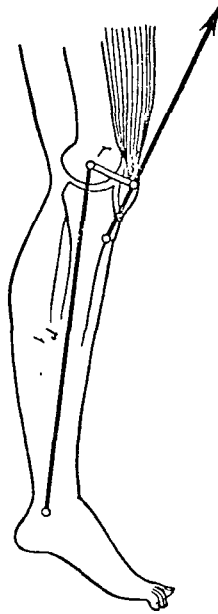


Figure 1

Scheme of the Action of the Muscle Extending the Leg in the Knee Joint (According to Donskoi); the Arm r of the Muscular Action is Considerably Shorter Than the Arm rl . The Arrow Indicates the Direction of the Muscular Tension.

The Concept of the Force Field

The movements of the human body or its separate sections always occur as a result of the interaction of external and internal (muscular) forces. The combination of these forces is called the force field. This term designates the direction and the magnitude of all the forces applied to the separate body sections which have specific degrees of freedom. The completion of voluntary action, by such a complex kinematic chain as an extremity of the human body, proceeds in a very complex field of force. In Figure 2 we show, as an example, two positions of the body sections of an expert athlete during a long distance run. Position I -- immediately after the raising of the leg at the beginning of the mid-air interval; Position II -- in the middle of the mid-air interval (after 0.08 seconds). It is evident that during this period the field of force sharply changed. In addition, the vector of force

applied at the center of gravity of the shin of the leg, which is /26
located at the back (in position I), is directed not to the rear-
up - as is to be expected, since the leg is being bent in the knee joint
- but ahead-down. This is explained by the necessity of braking the
shin and the foot, so as not to permit them to go too high, but to
follow the given trajectory exactly.

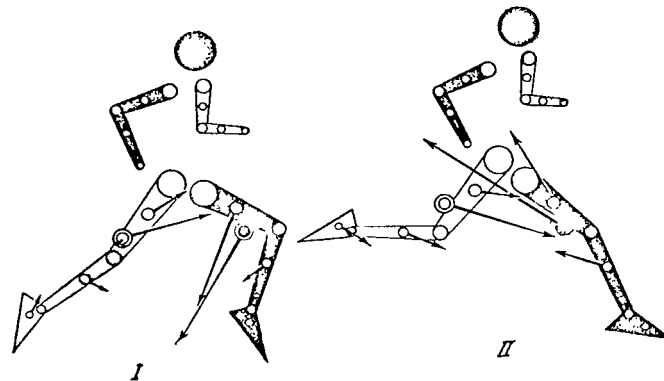


Figure 2

Change in the Field of Force (Vectors are Marked with Arrows)
of Leg Sections During a Run of a Highly-Qualified Athlete
(According to Bernshteyn).

The complexity of the field of force is due to three important causes:

1. The presence of multi-sectioned kinematic chains, which are mostly open in the course of the movement. These chains comprise the extremities.

2. The presence, in these chains, of exceptionally large numbers of degrees of freedom. The mobility of the tip of the fingers (in relation to the chest) is distinguished in man by 12 degrees of freedom; the wrists (in relation to the shoulder blade) -- 7; and the total number of degrees of freedom in the entire body -- a tri-valent number. Whereas, not one artificial mechanism created by man usually has more than three or four degrees of freedom. It is easy to see what demands are made upon the control mechanism by this complex structure of our extremities.

3. The presence of reactive forces. These forces occur in some section of the extremity as a result of its interaction with the adjacent one.

The presence of the reactive forces in motions is easily traced, for example, during simple walking or running. The predetermined extension of the leg in the knee joint always involves the lowering of the hip. A

biomechanical investigation of this question established the fact that this is accompanied by wave α , observed in the velocity vector of the knee joint motion (Figure 3). This wave is purely mechanical, since /27 an analogous phenomenon can be observed in leg prosthesis during an analysis of walking, if the knee lock is opened and the mobility of the lower part of prosthesis is secured (Bernshteyn, 1940).

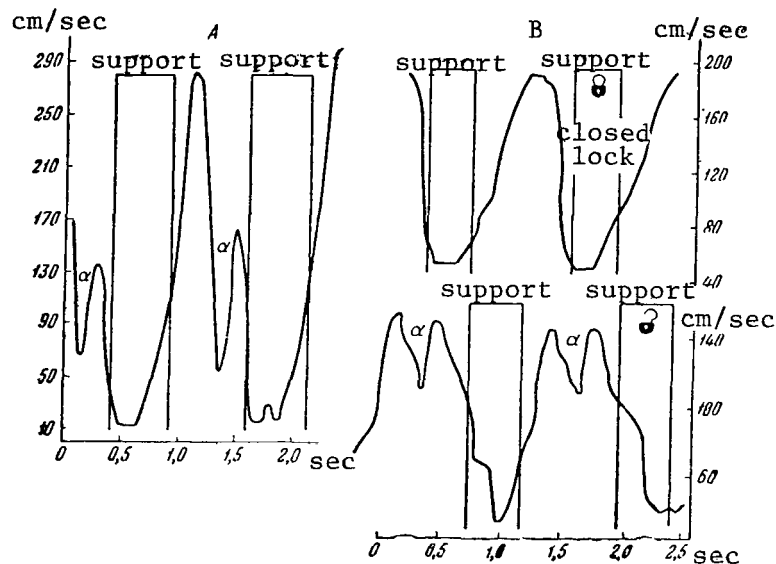


Figure 3

Reactive Wave α in the Longitudinal Velocity Components of a Knee Joint During Walking of a Man with Unilateral Prosthesis. On the Healthy Side, (A), This Wave is Always Observed (According to Bernshteyn); on Prosthesis Side, (B) Only for Open Knee Joint.

In well-developed movement, the reactive forces are not only barely noticeable, but more than that - as was indicated by numerous observations, including our own (Chkhaidze, 1957, 1958) - they are actively and positively involved in the movement itself, in addition to that outer simplicity and ease which the athletes call "relaxation" (although one cannot speak of any asthenia; it is simply that the reactive forces, by their participation in the movement, considerably facilitate the muscular effort). However, when fulfilling a new, unfamiliar movement, these forces, on the contrary, almost always hinder its true course. This makes it necessary to neutralize them, which, in turn, requires the cancellation of the corresponding degrees of freedom of the separate sections, and, consequently, additional muscular effort. As a result, usually a new, unfamiliar movement not only proceeds with great muscular expenditure, but is completed, it is said, "rigidly" and "tensely".

Our survey started with an examination of the force field of movement, since it ensures its kinematics, but it is the latter which is the most noticeable and apparent, both for the performer and for the person observing the movement. In other words, the entire central control of movements is constructed in such a way as to ensure the displacement of the sections in a specific area and during a specific period. In this way, the mental part of movement is easily controlled, and, consequently, it is easier to estimate it according to kinematics than according to dynamics, the many details of which are often deeply hidden from external observations. Nevertheless, even this part of movement coordination presents a number of difficulties which are entailed in its control.

If the motion of the body and its sections in space is related to the degrees of freedom for the sections (that is, to the mobility of the joints) then the duration of the movement depends on the speed of its completion, as well as on the temporal distribution of the section motion, separately and together. The latter is the most complex. The problem lies in the fact that the movements of the body sections are performed with both positive and negative accelerations. Very often there are situations when one section is accelerated, and the other either remains fixed, or even slows down the movement (see Figure 2).

In this manner, the kinematics of voluntary movement has a complex interrelationship with its dynamics. But since, as we have stated, kinematics is more apparent to the outside observer, it is there that the analysis of movement is usually begun (this was so historically). However, from the material we have presented, it is clearly evident that it is impossible to limit the study only to the first derivative motion - i.e., to the rate of movement of the sections with respect to time (the usual error of many researchers of voluntary movements). The activity of the central nervous system (and this is what is more important) can be adequately clarified in detail only according to the second derivative (acceleration).

Relationship Between Muscular Stress and the Resulting Movement

The question of the relationship between muscular stress and the resulting movement has been investigated since the latter part of the century. In addition, the initial investigations of Braune and Fischer (1895) indicated that it would be completely wrong to consider the amount of resulting movement as being proportional to muscular stress. However, the idea advanced by these investigators - that the acceleration of the center of gravity, of a section or of the system, is proportional to the muscular stress - did not last too long and was replaced by another viewpoint - that the resulting moments of force in the joints are proportional to 29 the muscular stress. This position was substantiated in considerable detail, first by Braune and Fischer (1904) and later in the initial works

of N. A. Bernshteyn (1929). However, his later investigations led to the conclusion that this formulation could not cover the entire diversity in the interrelation between the muscular stress and the resulting movements. This was particularly true for a study of motion during sports. A number of cases were discovered, when during flexing, muscular movements, which were significant in terms of magnitude, were directed to the opposite side (see Figure 2), and conversely (for example, in the leg sections, after the backward thrust in running, in hitting a ball, etc.). A mathematical analysis of these phenomena led to a new description of the interaction between muscular stress (and the moments of force expressing it quantitatively) and the resulting movement: this interaction is described by a differential equation of not lower than the second order (Bernshteyn, 1935, 1947).

Thus, we have here a complex and unusual relationship between muscular stress and the resulting movement.

Regimes of Muscular Function

As is known, the regime of muscle function can be very diversified. Physiology has compiled a great deal of material on this subject. These regimes are divided into three basic parts: the isometric, when muscular stress takes place under conditions in which the muscle length is retained; isotonic, when the stress takes place invariably with a decrease of the muscle length (almost always visible); and the auxotonic, when muscular contraction occurs under conditions of a certain preliminary stretching. The functional characteristic of the last regime is that, in view of the laws of irritability, the excitation of a muscle under these or other conditions of preliminary stretching can evoke completely different stress, and the muscle can function in a different manner.

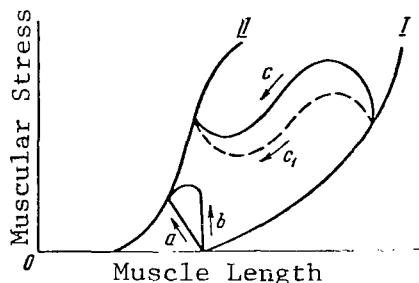


Figure 4

Diagram of the Lengths of Muscular Stress When Functioning Under an Auxotonic Regime (According to Bernshteyn). See Text for Explanation of Letters.

Figure 4 shows a diagram for the dependence of muscular stress on its length. The line a represents an ideal case of simultaneous contraction of

a muscle and an increase of its stress; curve c indicates the contraction of the muscle during lifting of a medium load at a fast rate; curve c_1 /30 characterizes the change, in this case, of the inert resistance of load; curve I -- a diagram of the mechanical stretching of a non-excited muscle and curve II -- stretching of an excited muscle.

The curves indicate that the muscular stress, necessary for a given movement, is a function of the minima of two independent variables -- its physiological state (determined by excitation) and its actual length at a given moment (determined by stretching).

If we take the fact into account that in a living organism, during the performance of a voluntary movement, the muscles almost always begin their action by one or another degree of stretching, then there must be no doubt that this also must be one of the difficulties entailed in controlling any movement, since - after initiating it - the central control apparatuses must take into account the degree of preliminary stretching of the muscles and apply the necessary excitation to them. That is why it is necessary to have detailed information on the muscle state "to make" the necessary decisions. We shall dwell on this question in more detail, later.

Dynamic Stability of Movement

Up to this point, we have only touched on the specific, physical, (biomechanical) factors determining the problems confronting the coordination of movements. Let us now examine a number of questions related to movement as a whole.

As we pointed out in the introduction, any voluntary movement involves a figurative problem. This encompasses those goals which are placed before the movement.

However, whatever the figurative problem of movement may be, it is accomplished by specific muscular synergy, whose activity is largely undetected. We are interested, first of all, in the quality of the performance of movement. This essentially represents the applied purpose of experiments on coordination of voluntary movements -- experiments related not only to the theory of the question, but also to a wide complex of pedagogical problems (training, perfecting, and transformation of the motor skills).

The attempt to determine the biomechanical qualities of executed movement, and to make a specific estimate of them led to an understanding of dynamically-stable movement. This term designates movement, which is mastered to such an extent that it is executed with a minimum of muscular expenditure, and which follows stable trajectories, both as a whole and in detail. Stable trajectories are assumed to be those which, after numerous repetitions, are easily reproduced by the performer, in space and in time.

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It is natural that any motor skill must be perfected before this state of development is reached (the entire theory of the question must cover exactly this point), but, in order to achieve this, it is necessary that all of the most important reactive forces, which occur in the extremity sections during the execution of a particular movement, take a direct and positive part in it (that is, they are instrumental in its correct performance). It is also necessary that all the necessary degrees of freedom are released, and the unnecessary ones are cancelled. Finally, it is necessary that the muscular forces exactly correspond to the conditions specified by the movement field of force. Thus, the given conditions must be observed not only at the beginning of movement, but throughout its entire course.

The determination of the concept of movement coordination as a whole follows from this.

According to N. A. Bernshteyn, "the coordination of movement represents overcoming the superfluous degrees of freedom of a moving organ and its transformation into a controllable system". Here, however, it is necessary to take the fact into account that we are not talking about the fixation of excessive degrees of freedom, but about utilization of them for the movement itself.

Observations have indicated (Bernshteyn, 1940) that, in order to obtain dynamically-stable movement (i.e., to master an unfamiliar skill), the central nervous system consecutively passes through three control stages (examining this from a biomechanical viewpoint).

The first stage: The initial phase of mastering a motor skill. In a kinematic chain, by means of muscular fixation, all of the basic, excessive degrees of freedom are cancelled, in order to neutralize the reactive forces which prevent the execution of the movement, over even an approximately correct trajectory. The movement as a whole is tense and heavy.

The second stage: The intermediate phase. After some mastering of the movement, a number of the excessive degrees of freedom are gradually released, since the reactive forces impede them to a lesser extent, and the impeding ones are extinguished by short impulses of muscular effort. The movement itself proceeds more easily and steadily than during the first stage.

The third stage: The final phase. The completely-mastered movement utilizes not only the muscular forces, but also the reactive force of the adjacent sections, based on the complete release of the necessary degrees of freedom.

It can be readily seen that the mastering of movement, in turn, presents the central nervous system with a number of complex problems, whose solution demands great flexibility in its functioning.

We are employing this term to designate those dynamic components of movement structure which - not being expressed sufficiently well - occur in view of the necessity to perform movement in a strictly physical manner, and in the most advantageous way. These components, as a rule, are not perceived by the person executing the skill, but are present in the movement structure in some form.

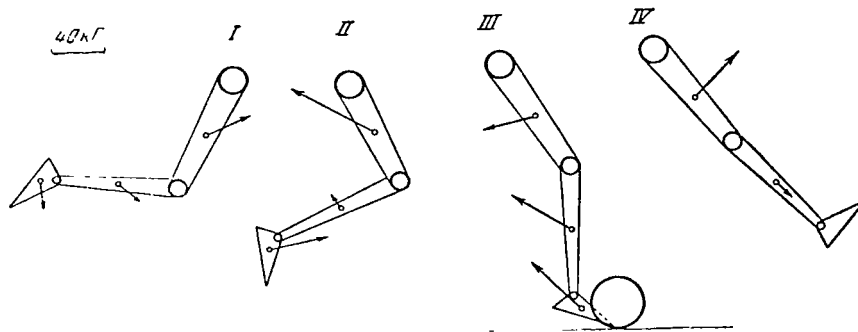


Figure 5

Direction of Forces Applied to the Gravitational Center of the Leg Sections of an Athlete Executing a Ballistic Movement (Football Players Kicking a Ball). Original.

I and II - Start of the Movement;

III - Moment at Which Foot Contacts the Object Being Hit

IV - After the Hit

Therefore, they can only be detected in those cases when the structure of the skills, executed within the limits of the neuromuscular stress, (for example, in difficult athletic movements, etc.) is examined.

In investigating the ballistic movements of athletes, we discovered what appeared at first glance to be a completely paradoxical phenomenon. If, at the start of the execution of any such skill, all of the forces applied at the gravitational center of the sections of the kinematic chain executing this movement (arm or leg) - as is indicated by Figure 5 (position I) - are always directed toward the course of movement, (which logically only indicates the initial acceleration of the corresponding sections), then - just prior to the actual contact with the object being hit - these forces, without fail, change to a reverse course. It is no less logical to assume that this could never take place (Figure 5, position III), since the change in the force direction involves the retardation of arm or leg sections, and this, at a first glance, is completely inadmissible in the performance of a ballistic movement. Physiologically, the activity of antagonists corresponds to this retardation (completely /33 passive in the first phase of movement), which can be traced very well in recordings of the bio-electric potentials of corresponding muscles (Figure 6).

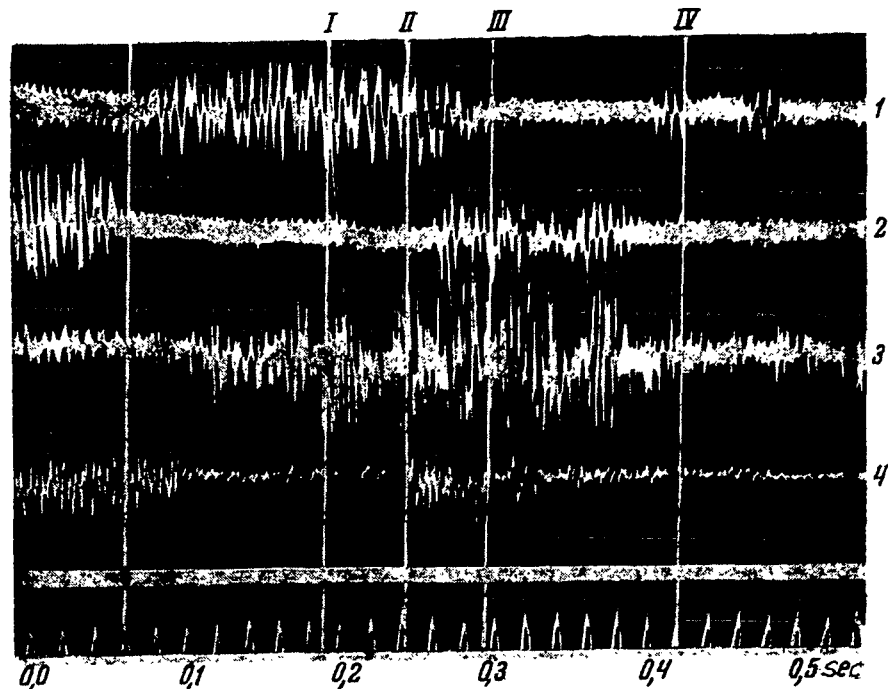


Figure 6

Bio-electric Activity of Leg Muscles of an Athlete Executing the Movement Reproduced in Figure 5. Original.

(1)-upright tip of the musculus quadriceps femoris; (2)-musculus biceps femoris; (3)-musculus tibialis anterior; (4)-musculus gastrocnemius

Vertical lines I, II, III, IV correspond to the positions illustrated in Figure 5.

However, the described phenomenon has very specific physical causes. The situation is that, in the execution of any blow, it is very important to transform the soft kinematic chain of an arm or a leg into a single, rigid lever (to make it, so to speak, into a "stick" for a short period of time). This has two physical advantages. First of all, the blow will involve not only the mass of the end section of the chain, but also all of the other sections as well (which makes it possible to considerably increase the mass of the striking object). Secondly, having changed into such a rigid system, the kinematic chain of the extremity, in the most decisive moments, will not absorb the shock, and consequently, will transmit to the object /34 being hit the maximum possible amount of kinetic energy, which has accumulated during the pre-swing. Such strengthening of the entire moving

system can be performed most advantageously through its sharp retardation. Therefore, at the moment prior to the contact of the foot or the hand with the object being hit, the antagonists start up, and a "paradoxical" change occurs, which is characteristic for ballistic movements, in the direction of the forces applied to the gravitational center of the chain sections which execute these skills.

Something similar can be also observed during the execution of other movements. For example, V. S. Gurfinkel (1955) traced the activity of antagonists and synergists of a leg in the supporting phase during simple walking. The biomechanical appropriateness of this phenomenon, which has also been observed by us (Chkhaidze, 1962) consists of the necessity of changing the kinematic chain of the leg at this moment into an unusual "column" which, by acting as a support, makes it possible to accomplish the pushing-away phase in a more economical way.

However, the most interesting element in the described phenomena is their complete imperceptibility by the performer. No one executing a ballistic movement has any idea of the fact that, at the most decisive moments -- prior to contact with the object to be hit -- all of the moving sections of the arm or leg, are retarded for a short period of time. This always takes place, and the movement (if it is mastered adequately well) is executed correctly and reaches the prescribed goals. The question thus arises of how to ensure the necessary biomechanical appropriateness of any movement (not only of ballistic movement). It is assumed (more will be said on this later) that it is produced by the corresponding interaction of the muscular extremities, which, in turn, depend on the activity of the central apparatuses controlling the particular skill.

* * *

As follows from all the preceding statements, control of voluntary movements in man (and higher animals) represents a very complex problem. The problem consists of changing a number of kinematic chains which are in themselves uncontrollable into a controllable system.

This complexity is produced by an immense amount of degrees of freedom, the presence of reactive forces, the complex interaction and ambiguity of the connection between muscular stress and the resulting movement, and the auxotonic function of the muscles.

In order to solve this grandiose problem, it is natural that there must be a very complex, carefully-differentiated apparatus, which has passed through the stern school of evolution and which is capable of examining any variants set forth by life.

GENERAL SCHEME FOR CONTROLLING VOLUNTARY MOVEMENTS IN MAN

As we mentioned earlier, any voluntary movement of man is affected /35 by the interaction of the operation of specific groups of muscles, by the apparent conditions of the motor problem being solved, and by the general force field of the movement. This interaction provides the particular sections with the necessary acceleration and the required trajectory of movement.

On the basis of the nervism principle, it must be assumed that this is effected by strict continuity in the operation of nerve cells in the brain centers controlling the particular muscles. Evidently there is a well-defined, interrelation between the state of the nerve centers and a change in the excitation of the muscles. The movement itself can be regarded as a certain control process where the controlling section is the central nervous system, and the controlled sections, in the final analysis, are the parts of the body.

According to the teaching of Sechenov--Pavlov, the development of a specific skill is due to the formation of temporary relationships between the various centers of the brain.

The formation of temporary relationships is usually divided into three phases.

The first phase represents the phase of generalization. This is characterized by the dissemination of the excitation to many sections of the cortex.

The second phase is distinguished by considerable dissemination of internal inhibition, which excludes the excitation of unnecessary cells and in this way restricts it.

The third phase represents stabilization of excitation when it encompasses only the nerve centers which are most indispensable for excitation of the necessary nerve fibers. It can be readily seen that this corresponds in many ways to the sequential manner (which was mentioned above) in which the motor skills are mastered, from the bio-mechanical point of view.

It follows from the statements given above that the sequential nature of excitation and inhibition of nerve centers is not accidental, but is related to a specific mechanism which can be justifiably called a program of movement, and the development of a skill can be regarded as a product of this program.

However, as we indicated, the correct execution of a movement is too complex for any program to encompass its total control.

We shall, therefore, attempt to represent the course followed in the central control of voluntary movements, taking into account not only the narrow physiological factors, but also the physical (biomechanical) factors. This is easily seen in the general scheme illustrated in Figure 7. This question encompasses too much material which has not been studied, and therefore this type of a scheme cannot be developed without including a certain hypothetical part. However, in examining the location of ganglions, we can base our investigation on established physiological rules and the most important principles underlying the operation /36 of the control systems.

- (1)-Thinking; (2)-Motor Memory; (3)-Brain; (4)-Checking Mechanism of the External Reverse Connection; (5)-Assigning Mechanism; (6)-Programming Mechanism; (7)-Checking Mechanism of the Internal Reverse Connection; (8)-Synthesis; (9)-Servo-Mechanism; (10)-Direct Connection (arrow); (11)-Spinal Cord; (12)-Synapses; (13)-Muscles (Motor); (14)-Coding; (15)-Body Sections; (16)-Vision; (17)-Hearing; (18)-Olfaction; (19)-Touch; (20)-Taste; (21)-Transmitters; (22)-Proprioceptors (Transmitters); (23)-Exterior Environment; (24)-External Control Cycle; (25)-Internal Control Cycle; (26)-External Reverse Connection; (27)-Internal Reverse Connection.

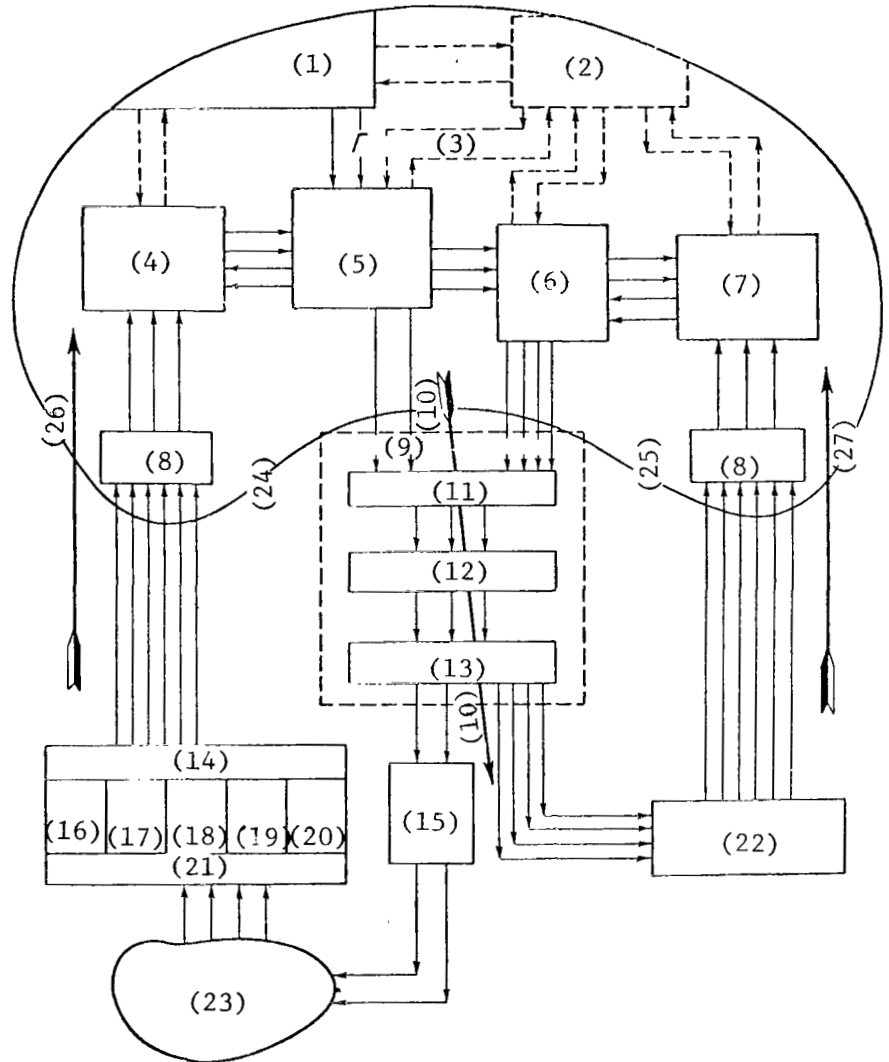


Figure 7

Hypothetical Scheme Showing the Passage of Information During the Regulation of Voluntary Movements in Man. Original.

The first, most fundamental rule in the coordination of movements is the presence of the "control cycle" - in other words, the dependence of not only the controlled section on the controlling ("direct connection") section, but also conversely ("reverse connection"). /37

As a result of the dynamic complexity of voluntary movements, it should be assumed that it is not possible to achieve coordination of movements without the central nervous system having complete and exhaustive information on what is taking place along the periphery. The existence of this informational apparatus is not denied by any of the modern physiologists, who call a similar process, proprioceptive afferentation, or according to P. K. Anokhin (1957), "reverse afferentation". A great deal can be stated about the role and significance of this apparatus, which, in our opinion, is underestimated to a certain extent by many investigators.

On the other hand, it is well known that during simultaneous disturbances of the extero- and proprioceptive sensations, rational achievement of a sufficiently complex voluntary movement is impossible. It can be assumed that the control of such movements is achieved through a closed cycle: brain---centrifugal nerves---muscular synapses---muscles---proprioceptors---centripetal nerves---brain. In this cycle, the area of direct connection will be, brain---muscles: and the reverse connection, muscles---brain.

However, after a more detailed examination, this "cycle" is mainly divided into an internal and an external (see Figure 7) portion. "The external cycle" includes the direct connection and the external arc of the reverse connection along the visual, auditory, olfactory, and tactile receptors, which have figurative afferentation and are directly related to the perception of the outer world. "The internal cycle" includes the direct connection and the internal arc of the reverse connection, along the proprioceptors which are not directly related to our consciousness.

In this manner, the common part of the "cycles" is the direct connection (brain---muscles). This division of "cycles" is very fundamental: they each play a different role in controlling the voluntary movements. It must be assumed that the "external cycle" controls the thinking part of the movement, and the "internal ring" -- the synergic automatisms.

It is well known that the higher divisions of the central nervous system have a comparatively small afferent relationship to the muscular periphery, while the lower divisions, on the contrary, display this relationship to a full extent.

To illustrate this point, we have shown a scheme borrowed from the book by N. A. Bernshteyn, The Structure of Movements (1947) in Figure 8.

As is indicated by the scheme, the following tracts lead from the brain to the periphery: the pyramidal tract (Pyr), which originates

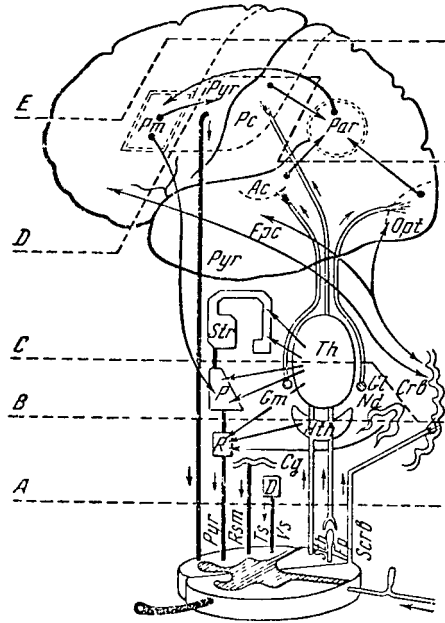


Figure 8

Scheme Showing the Location of the Basic Nuclei and Conducting Tracts of Man's Brain (for Easier Viewing, the Location of the Nuclei was Greatly Distorted) (According to Bernshteyn).

at the higher divisions, and a group of extrapyramidal (Rsm - rubrospinal, Ts - tectospinal, Vs - vestibulospinal), which originate in the lower divisions. Only one group of tracts leads from the periphery to the /38 center (Sth - spinotthalmic, Fp - posterocolumnar, Scrb - spinocerebral); they terminate at the lower divisions. The tracts Fpc - frontopontocerebral and occipito-temporopontocerebral connect the higher divisions of the brain with the cerebellum. Simultaneously, the scheme indicates the possible distribution of the basic brain nuclei according to levels: R - red nuclei; D - Deiter's nucleus; Gg - lamina quadrigemina; Hth - hypothalamus; Nd - dentate nucleus; P - pallium; Gm - mediale and Gl - laterale geniculatum; Crb - cerebellar cortex; Str - striatum; Th - optic thalamus; Pm - premotor zone of the cortex; Pyr - pyramidal area; Pc - postcentral gyrus; Ac - auditory zone; Opt - optic zone; Par - parietal area. The arrows indicate the connections between the single nuclei, and the dotted lines indicate the possible location of the levels for controlling movements.

It can be assumed that the information on the course followed by the specific synergetic elements of movement does not reach the "external control ring", since it is not connected by reverse connection to the separate muscular units. This, and consequently the control of such

elements, is entrusted to the lower divisions of the central nervous system, which - belonging to the "internal control cycle" - have the necessary tracts. Only an integrated signal can enter the "internal cycle".

This division of functions is observed in the execution of a mastered movement. If a movement unfamiliar to man is being executed, and the lower divisions are not completely prepared to control it, then in this case the higher divisions control the mental part of the movement, and the specific synergetic elements either are not controlled or, as a last resort, are controlled to a minimum degree by the higher divisions. Since, under these conditions, the higher centers perform two functions, one of which is clearly unnatural for them, they can do this only in a very primitive form, controlling the course of the movement by means of external receptors - that is, through the external reverse connection. As a result, the movement itself is also executed primitively, as was described in the first chapter. This phenomenon is well known to everyone trying to master a new, unfamiliar motor skill. /39

Complete control of all of the specific elements of movement (and, consequently, its qualitative performance) occurs only after the lower divisions form the proper connections between the cells and the centers, and make the internal reverse connection efficient. In this way, the "internal cycle" will be included in controlling the movement, and the higher divisions (that is, the external cycle) will be left with their immediate problem -- control of the mental part of the movement.

Only then does a biomechanically-correct decision as to the finest elements in the mental part of movement become possible.

The division of the "control cycles" and the reverse connections into external and internal parts is, in principle, related to the question of programming movement.

All of these statements indicate the existence of an apparatus which provides for this programming. However, it must be mentioned that, in spite of the obscurity of many aspects of this question, even now it is possible to differentiate this apparatus in certain ways.

It has been established that all of the higher animals who have been deprived of the higher divisions of the brain (for example, the corresponding divisions of the large hemispheres), because of trauma or for other reasons, are completely incapable of solving the mental problems of movements, but can easily perform even complex automatisms (for example, walking), if these movements were mastered before the trauma (Bernshteyn, 1947). On the other hand, it is known that pathological changes in the conducting tracts of the internal reverse connection (for example, tabes dorsalis, which results in the regeneration of the posterior columns of the spinal cord) leads not only to a disturbance of the habitual

automatisms, but to the complete impossibility of executing the movement without visual control - whereas the general mental part of it remains undisturbed (there also).

Consequently, if the "external control cycle" is disconnected, it is possible to perform the movement elements under the control of the "internal cycle", and if the "internal" is disconnected - under the control of the "external". In both cases, the movement loses some elements which were controlled by one or the other "cycle". On the basis of these facts, it is possible in the first approximation to /40 single out at least two stages of programming.

The first, consisting of the solution of problems related to space, time, and speed of movement (i.e., to the basic problems of its mental part), is entrusted to the higher divisions of the central nervous system, and this stage can conditionally be called the assigning mechanism. The second stage, which determines the course followed by the movement in the elements - i.e., which establishes a sequential pattern in the specific muscular synergia, etc. - is entrusted to the lower divisions which can be very correctly called a self-programming mechanism, since programming - used in the sense of cybernetics - is exactly what is done here. We shall try to clarify this in more detail further on. In any case, it can be readily seen that "the external control cycle" is largely related to the first stage -- the assigning mechanism; the "internal" is largely related to the second -- the programming mechanism. Both mechanisms, in performing a well-mastered movement, function in succession. However, in the training process and in some pathological states, the additional problem of controlling some small, specific elements of the movement falls on the assigning section, although its biomechanical side is not prepared for this. This occurs because an adequately-effective "internal control cycle" has not yet formed. In any case, the presence of the two basic nerve tracts mentioned above - the pyramidal and extrapyramidal - in the brain does not make it impossible for the central nervous system to control a movement through both cycles giving preference to one or the other of them when required.

We should add the following to the statements given above: first, although we have conditionally examined the compilation of a program in stages, the actual development of it has evidently a different character. In the assigning mechanism it is developed throughout all the movements from their beginning to the end. In the programming mechanism, it is developed during the course followed by the movement, depending on the correcting signals transmitted from the checking mechanisms of internal reverse connection. Secondly, the actual division of the central apparatuses has in many ways a conditional aspect. It can be assumed that the higher is the automatization of the skill, the higher must be the divisions of the brain which perform the role of the assigning mechanism. Conversely, the less the skill is mastered, the more these apparatuses need to work out the explicit elements of movement. In other words, the "assigning" or "programming" mechanism cannot permanently belong

to specific divisions of the central nervous system. On the contrary, depending on the degree to which the skill is automatized and the problems confronting the movement, the role of these mechanisms can be fulfilled by its different subordinate levels.

In addition, the scheme under consideration does not all assume /41 complete independence of the "internal cycle". The integrated signals of its operation must always be transmitted to the "external cycle". The basic function of the "second cycle" is to secure the biomechanical appropriateness of movement (which is developed by prolonged training), but it cannot independently solve the mental problem. On the contrary, the "external cycle" only ensures the highly-coordinated solution of the mental problem when the "internal cycle" is fully prepared for this. It is then possible for the "external cycle" to develop the finest mental elements of movement correctly. This phenomenon is well known, for example, to musicians and athletes. Only by good mastery of the biomechanical part of the movement being learned (i.e., by establishing the operation of the "internal cycle") are they capable of transmitting the finest shades of musical composition or of achieving a motor skill within the limits of man's capabilities. It is very interesting to note that this is directly perceived by man to a great extent.

After the program of movement is predetermined in the "external cycle", its accomplishment begins. In order to do this, the muscular periphery must be placed in a state of physiological excitation.

It can be readily seen that the "two-cycle scheme" (Figure 7) for controlling voluntary movements is essentially (like any other control scheme) a scheme for the transmission of information in the human organism during the execution of voluntary movements. In this case, within the organism the information is transmitted along the nerve axons from the brain to the muscles. This represents the direct connection. The information transmitters of reverse connection are, similarly, proprioceptors, axons, and brain.

Outside the organism, information can be transmitted by means of light fluctuations, air fluctuations, etc. - i.e., by all stimuli of our external receptors.

In this way, the important physiological concept of "stimulus" acquires an additional (for this case) designation of "control information". Thus, the term stimulus designates not only the external stimuli, but all of the internal ones, which control movement or other physiological processes.

To provide a more exact definition of these statements, the "external control cycle" can be distinguished as a cycle for transmitting information, in which one part is located entirely outside the organism. The information which proceeds along the "internal cycle" does not pass beyond the limits of the organism. Here, the flexibility of the human organism

is revealed as a self-controlled system. When the mastery of a move- /42
ment is guaranteed, it is controlled "within" the organism, and in
this way its performance has maximum protection from random effects
of the environment. When it is necessary to take into account the un-
predictable effect of the environment, the external connections are
included in the control chain.

The function of the analyzers can be represented as the function of
certain coding mechanisms.

An investigation of all of the patterns presented here represents a
project of the future, but, as we have already mentioned, it can be
assumed that information is evidently coded along a dual system. It
must be mentioned that, as is known, such a system is the simplest to
organize, out of all the possible systems which can be applied for
analogous purposes.

An important part of the mentioned mechanism is the spinal cord, and
possibly some of the lower divisions of the brain. The terminal part of
the control system is represented by the nerve endings in the muscles --
the neuromuscular synapses. It is there that the final transmission of
information to the muscles takes place.

After the information reaches the periphery and produces excitation
of the appropriate muscular fibers, muscular stress occurs. The first
part of the problem confronting the central nervous system - the effector -
problem - will then be completed. The necessary force created by the
stress of these muscles will be applied to the extremity sections, which
are connected to the stimulated muscles and are necessary for the execu-
tion of the specific movement. A reorganization of the force field will
begin and, consequently, the movement itself. From this moment on, the
central nervous system takes over another, not less important, part in
controlling movement, the afferent part - the control over the course it
follows.

The accumulation of primary data from the internal reverse connec-
tion, from afferentation, is performed by the proprioceptors, the nerve
endings in the muscles and tendons ("transmitters" of the internal reverse
connection), which, as was mentioned above, transmit this information to
the central brain divisions along the corresponding centripetal axons.
Thus, information on the physiological and mechanical state of the muscles
is transmitted by the muscular proprioceptors; information on the joint
angles (on which all of the most important information on the speed and
movement acceleration of a section in space is based), is transmitted by
the tendinous and the articular proprioceptors. After synthesis and,
evidently, recoding this information enters the checking mechanism.

At this place, an important meeting between the information, which
is furnished by the reverse connection and the information-command takes
place. In this area, new signals are developed which again enter the

"control cycle" through the direct connection. The connection between the muscular stress and the resulting movement is expressed by a differential equation, of not less than the second order. /43

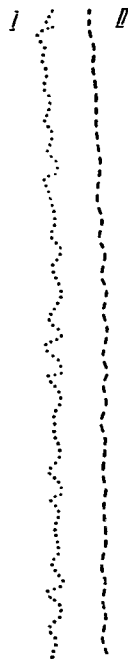


Figure 9

Kymocyclographic Recording of the Wrist Movements of the Right (I) and Left (II) Hands During Intensional Tremor (According to H. A. Bernshteyn).

This means that in the course of the movement, depending on the changing position of the sections, these equations can have a multiplicity of solutions, out of which one - which more or less satisfies the conditions of the particular motor problem - must be selected in order to compare it with the actual state of affairs and, finally, to introduce the necessary corrections in the course of the movement.

In other words, the checking mechanism accomplishes the helpful effect of the reverse connection.

It can be seen from the statements given above that the checking mechanism is necessary. The problem of its localization is far more complex. Some data on its location can be obtained from investigating a number of pathological states.

It is well known that the signals of the checking mechanism can cause not only the stabilization of the control system, but also its disorganization. This occurs when the signal, which originates in the checking mechanism and strives to restore the system which has deviated from the required position, is too great or is not well-timed. Thus, the system returns to the state of equilibrium with such force that it "jumps past" it, i.e., as we say, it "roams". Something similar to this type of "roaming", in the form of an intensional tremor, is observed in multiple sclerosis in cases of cerebellum damage. Figure 9 shows a kymocyclogram of such a tremor.

It is evident from the illustration that arm fluctuations are very similar to the analogous phenomena observed in artificial systems when the stabilizing system is mismatched. In our opinion, these data can serve as a starting point for a thorough investigation of the localization of the checking mechanism of internal reverse connection (Viner, 1958). In regard to the question of the checking mechanism of the external reverse connection, its operation in man is generally well-known. In executing any movement, we always, or almost always, follow its performance by external receptors. The presence of such a mechanism in animals was well demonstrated by L. V. Krushinsky (1959) who called this activity the extrapolation reflex, and established a number of rules connected with it. He determined, in particular, that animals plan their movements with great precision, making "corrections for a /44 change in objective", roughly speaking. It is clear that this is impossible without the normally-functioning, checking mechanism of external reverse connection.

We shall discuss the checking mechanism of the internal reverse connection in greater detail later on. We would like to note at this point that - as we have pointed out - since the basic problem encountered in the coordination of voluntary movements is to control a very complex kinematic system, and thus to ensure the most correct execution of the movement - and since this is primarily determined by reciprocal amounts of tension between muscular synergies which interact with the periphery in a very complex manner - it must be admitted that it is in both checking mechanisms where the principal work of movement control takes place in its full complexity.

Let us illustrate this with an example. The prevention of the "roaming" described above occupies a central position in the calculation of closed control cycles, and normally succeeds only in limited locations of the input parameters. The exceptional stability of human movements under the most diversified conditions thus seems all the more astonishing. This stability is ensured by only the most precise operation of the checking mechanism. This is the reason we consider it to be so important.

Our scheme also makes provision for the presence of the so-called "motor memory". The existence of this apparatus cannot be doubted, because its functions are quite obvious, both for the "external" and the

"internal cycle" of control. However, its localization is in great doubt. It is very dangerous to draw any analogy here with calculating mechanisms. At the present time, the pathological conditions are unknown which disturb the motor memory functions, without disturbing the functions of the assigning and programming mechanism. Therefore, another assumption can be made to the effect that these mechanisms concentrate in themselves the collected experience (i.e., they retain the movement program in the form of more or less stable connections). However, taking into consideration the most extensive possibilities of our organism, we conditionally select the motor memory block as being possible for certain very complex types of movements or combinations of movements.

Our scheme covers only the basic mechanisms which are directly connected with the perception of the external world and the control of movements. But it is impossible to conceive that such a complex system as our neuro-muscular apparatus - which, in addition, functions with the use of electric signals - has no special mechanisms or devices for suppression of noises and elimination of all other interferences characteristic for such systems. Regardless of the fact that the existence of such mechanisms apparently is beyond doubt, both their localization and their methods of functioning are unknown. The almost ideal noiseproof /45 nature of the normal organism is all the more astonishing. At any rate, it is impossible to draw a complete analogy and to assume that they represent integral apparatuses. The possibility is not excluded that they may possess forms totally unknown to modern science.

However, one method of fighting interferences is known -- the excess of information which is characteristic of living organisms. This means that the same informational function is performed by a whole series of elements, thus duplicating each other. Physiologically, this phenomenon is confirmed by vicarious properties of nerve calls. It is possible that it applies to other apparatuses and mechanisms listed above, whose existence we do not doubt. In conclusion, it must be mentioned that the reverse connection of the "internal cycle", in contrast to the "external cycle", apparently functions continuously. In other words, the central nervous system always possesses extensive information on the condition in the periphery, and initiates any voluntary movement in accordance with this.

In view of this and of all the statements given above, the general scheme of voluntary movement control can be presented as follows.

Upon receipt of a "command" from the highest brain divisions, the assigning mechanism determines the sequence to be followed by the movements of extremity sections, in accordance with the mental problem of the movement. The programming mechanism differentiates this with respect to concrete synergies, in agreement with the conditions at the periphery based on the internal connection data. The control signals, in a coded form, proceed along the efferent paths to the servomechanism, and set it in motion. The corresponding information continues to move along two

arcs of the reverse connection: along the internal one - through the proprioceptors, along the afferent paths to the checking mechanism of the internal reverse connection - and along the external one - from the extremities, through the surrounding medium to the external analyzers. After coding and synthesis, the information enters the checking mechanisms of the "control cycles", where corresponding corrections are made in the movement. The "external cycle" controls the mental part of the movement, and the "internal cycle" controls the automatisms, and regulates the movement in the synergetic elements. Simultaneously, memorization of the course followed in controlling the movement occurs - more precisely, memorization of the movement program - for the purpose of discharging the mental part of the movement control by prepared automatisms. This explains the ease with which unfamiliar movements are mastered in those cases when the performer possesses a great number of motor habits, and also explains that which is called the transfer of skill in sports and in education.

It should be mentioned that there may be many cycles participating in the execution of any one voluntary movement.

It is important to note that the sum value of overall muscular /46 contraction depends on the number of excited muscular fibers; a certain number of these fibers must be excited, depending on the magnitude of the required muscular exertion.

On the other hand, during muscular contraction, the mechanical influence will be exerted on all proprioceptor elements, without exception, which are located in a given muscle or tendon, whose strain determines the value of the joint angle. These elements provide information which enters the checking mechanism. The latter must provide some general evaluation of this information. Therefore, we assume that, before checking, the signals, which are fed from the receptors in order to make this evaluation, are processed. However, the principle underlying information processing in the checking mechanisms is so far totally unknown.

Thus, general evaluations are required for an accurate, differentiated programming of movement. For the external cycle, these evaluations must be extremely general in nature. It should also be mentioned that the greatest differentiation is observed in those cases when movement is most completely mastered qualitatively.

CERTAIN DATA ON THE OPERATION OF THE ASSIGNING AND PROGRAMMING MECHANISMS

At the present time, there are no accurate data which fully elucidate the operation of the assigning and programming mechanisms of the central nervous system during the control of voluntary movements. Only assumptions having a relative degree of validity may be made in regard to general

aspects of this subject. However, a discussion of the information collected in this field is justified, in order to present a clear picture of the existing situation.

The most detailed information is given in the work of N. A. Bernshteyn, "Construction of Movements" (1947). Although this work to a certain degree may be controversial, the collected material is useful for clarifying a number of very important questions.

According to N. A. Bernshteyn, it is possible to distinguish at least five increasing "levels" which are responsible for one or another motor task during the control of movements. The highest levels fulfil the role of leaders, and the lowest - of the background. Each one of them has its own function, localization, and - we must emphasize - afferentation. They are also inter-connected phylogenetically. The lowest, naturally, is of a more ancient origin, and the highest appears in the further evolution of the animal world. A description of two levels, together with an enumeration of the corresponding tasks and other indices, is given in Table 1. The possible localization of the levels is shown in Figure 8.

The operation of the levels is described, taking into account the /48 execution of complex movements (for example, writing, which consists of both symbolic coordination which is connected with thought expression, and the coordination connected with the motion of body sections in space). The highest cortical level (E), which controls higher symbolic coordinations, belongs more appropriately to the division of conscious thought. This is apparent due to the fact that its afferentation is not connected with the "internal cycle" of reverse connection, and fully depends on the "external cycle". Naturally, it always plays the role of the leading level. This level is, apparently, peculiar only to humans.

The level D, which is closest to E, the parietal-premotor ("objective action") level, solves the mental problem of a given movement, and builds connected movement chains. Afferentation of this level consists of a generalized synthesis of a "qualitative" nature, which is composed of external and internal information, i.e., it moves along both "cycles". Its role as a background member is very insignificant, but its leading role is quite extensive, and encompasses almost all automated mental movements.

The third level C is the "pyramidal-striated" level. The task of this level is to differentiate movement to a certain extent and to divide it into elements. The development of these elements is connected with definite movements which are most frequently encountered in life-movements which can, in certain cases, have an independent role. Such movements, for example, may include the simplest locomotions, etc. It can be readily seen that in some cases this level can assume an independent, leading role, and in some other cases - the background role.

TABLE 1
LEVELS OF MOVEMENT CONSTRUCTION

Phylogenesis	System Designation	Level	Basic Function	Possible Localization	Afferentation	Role	
						As a Background Member	As a Leading Member
Neokinetic	Pyramidal (Cortical)	F Higher cortical (group)	Control of higher symbolic coordinations (speech, writing, et.)	Frontal cortical portion of cerebral hemispheres	Complex mental	Does not apparently exist	Only leading
		D Parietal-premotor (objective action)	Solution of the mental task involved in the movement. Formulation of connected chains of movement. Movement with an object.	Parietal lobes and premotor regions of cerebral hemispheres	Telereceptorial	Very insignificant, only as an "ultra automatism" for symbolic coordinations	Quite extensive. Encompasses almost all mental movements
		2 C ₁ Pyramidal-striated (of a spatial field)	Body motion in space	Gigantopyramidal field. Striated body	Synthetic spatial field (developed teleproprioceptorics and tangential receptorics)	Extensive. Participates as background in mental movements, connected with body motion	Considerable. All of locomotion, ballistic movements, imitating movements, etc.
	Extrapyramidal (Subcortical)		Thalamic-pallid (of synergies) Control of muscular group synergies. Struggle with reactive forces. Creation of dynamically stable movement.	Optical nodules. Pale bodies.	Proprioceptorial and tangential receptorial	Quite extensive	Weak (expressive gesticulation, plastic movements, voluntary movements)
Paleokinetic		A Rubro-spinal	Control of muscular tone. Control of chronaxie	Red nucleus group. Spinal cord	Proprioceptorial	Basic /47	Insignificant (posture, involuntary movements)

This can occur, for example, if the executed locomotion (walking, running) itself, which is controlled by this level, begins to assume a subordinate role. Therefore, this level has an afferentation, which is developed in a complex manner and which is connected with both the "external" and the "internal cycle". In some movements, it may be observed that this level can be broken down into two sub-levels, C_1 and C_2 .

The task of the level B ("thalamic-pallid") is the control of synergies. But, since it is connected more directly with the muscular apparatus, the afferentation of this level depends on proprioception.

Bernshteyn assumes that the level A is the lowest in controlling elements of movement, and controls such elements as muscle tone and chronaxie. This level, just as the previous one, can only be a background element, and correspondingly possess only internal afferentation. However, the reservation must be made that, depending on the complexity of the movement, the role of the described levels may change to be either a background role or a leading role. This is related to the task of the movement, and the degree to which it is mastered by the performer; it is also related to the phylogenetic development of the central nervous system. The lowest animal forms may have the level /49 C, or even B, as the leading level. The same is also true with respect to ontogenesis.

The interrelation between the levels in controlling a "developed movement" occurs under conditions of subordination, i.e., the higher level controls the activity of the lower level. The purpose of such subordination is the correct distribution of roles among the levels, in order that each one of them solves the problem which most fully corresponds to its afferent possibilities. As we have already shown, the higher levels have no valuable reverse connection with the muscular periphery and, consequently, cannot perform the corresponding control over the explicit elements of movement. On the other hand, the lower levels, which do not resolve the mental part of movement, cannot be included in it independently; the operation of higher levels is required for this. Therefore, if an unfamiliar movement is executed, then - because of the fact that the lower levels are not prepared to handle it - its control falls entirely on the higher levels (primarily, the highest), which, naturally, are forced to exercise control over explicit elements in a very primitive fashion. As a result, the movements are executed in the manner described above.

It can be readily seen that the "development" of movement in this case amounts to establishing subordination, and, consequently, the mastery of an unfamiliar motor skill requires the formation of corresponding connections between divisions of the central nervous system. When the movement is sufficiently mastered, the lower levels will be delegated all tasks which are inherent to them, and the higher levels will be freed of inappropriate tasks, and the movement will take place in a more correct manner. In light of the above statements, the auto-

mated motor skill can be considered as one for which the background levels have completely mastered their tasks, and interference of the leading levels not only becomes superfluous, but even harmful⁽¹⁾.

The control of movements - for example, in the process of writing (we have used writing as a "multi-staged" act, which makes it possible to illustrate very clearly the operation of background levels) - may be represented as follows.

Level E solves the highest symbolic problems of movement - for example, "I have to express the following thought".

Level D determines the mental task of the movement: "I have to write certain words consisting of certain letters".

Level C distributes movements of hand and pen in space, i.e., it shows exactly how and where extremity sections move.

Level B distributes work between the muscular synergies (curves, speed, character of handwriting).

Level A ensures the corresponding muscular tone and the control of /50 muscular chronaxie.

Of course, the above description provides only an approximate picture of Bernshteyn's scheme for movement control, but we have retained most basic elements representing its principle characteristics.

In conclusion, it should be mentioned that the above description of movement control (which is, naturally, in many aspects hypothetical) is based on a certain amount of evidence.

CLINICAL STUDY OF ORGANIC BRAIN DISEASES

We already mentioned some facts; they are treated in greater detail in N. A. Bernshteyn's book (1947).

The essence of these facts can be reduced to an analysis of the prolapses of motor functions as a result of various diseases of the central nervous system.

Thus, for example, diseases of the central afferent path lead to an ataxia syndrome in spinal ataxy as a result of degeneration of the posterior columns of the spinal cord, which normally carry the entire

⁽¹⁾ It is a well-known fact, for example, that the interference of conscious action may ruin handwriting.

proprioceptor signalization. But since the levels A, B and C are related in one way or the other to these receptor qualities, all the well-known phenomena are readily explained by the prolapse of these levels.

In regarding the phenomena of hypodynamics and hyperdynamics, N. A. Bernshteyn establishes possible localization centers for control over general movements, taking the fact into consideration that its mental structure is always provided by the leading level of the given movement. Consequently, the loss of a certain function should become apparent when the control of synergetic elements changes to a higher level (which, in turn, is expressed in the change from one form of movement control to another), and this will point to the fact that a specific nerve center, which normally controls this movement, has been put out of service.

In order to simplify the discussion of this information, let us give one example.

Yu. A. Vasilenko describes an interesting case in "Proceedings of the 15th Session of Ukrainian Psychoneurological Institute" (Vol. XXIV, 1949), when a patient with symptoms of sclerosis of brain vessels (attack of the thrombosis type in the region of the IV-V branch of the central brain artery on the right side) developed tactile agnosia and unusual disturbances of the movements in the upper left extremity. The patient satisfactorily flexed and unflexed separate fingers and the entire hand, but as soon as the isolated movement became complex, its execution was sharply hampered: the patient could not feel objects, and could not satisfactorily tap the table with even one finger. He could execute other, simpler movements only with visual control. At /51 the same time, the muscle tone was not disturbed, although a number of other disturbances in the body indicated an injury at the right lower parietal region.

The author concludes that "the complex motor act of the patient dissolved into separate component parts, into more primitive fragments, which are characteristic of the lower level of the functional organization (our underscoring - L.Ch.), -- and into the total flexion of the hand and fingers".

It can be readily seen that in this case the operation of the sub-level C_1 (feeling an object) was disturbed. More primitive movements - such as, flexing and unflexing fingers and hand - were executed satisfactorily, because they were controlled by the lower centers which remained undamaged. On the other hand, as the author points out, other, simpler movements were performed only with the visual control. The latter points to the fact that the control of a given movement changed from the level C_1 to the higher level, possessing only visual afferentiation.

STUDY OF PHYLOGENESIS OF THE CENTRAL NERVOUS SYSTEM

If we followed the process by which the motor functions "grow" as animal organism becomes more complex and the control nervous system is simultaneously enriched, it could be readily established that both these processes take place simultaneously. The higher levels appear in the "animal scale" in direct relation to the increasing complexity of motor tasks. (Sepp, 1959.)

The course of evolution of motor act control can be readily traced in those remnants of control which remain in the functions of the lower brain regions, in the transition from lower to higher animal forms.

Indeed, it is a well-known fact that the chordate animals, including amphibians, lack those formations of the nervous system which are called the brain cortex in mammals. However, their movements lack neither dynamic stability nor lability because of this, which fact points to the possibility of forming new central connections.

Moreover, it is well known that in lower animals - fish, for example - cases have been observed in which it can be assumed that the basis of the locomotion rhythm (swimming) is the ability of the spinal cord to form the impulses required for this automatically. (Dzenit, 1936.)

Consequently, the ability of the sub-cortex centers in lower animals to control movements independently and, when necessary, to display vicarial characteristics cannot be denied.

STUDY OF ONTOGENESIS - DEVELOPMENT OF MOTOR ABILITIES IN A CHILD

In the development of the human organism, these levels develop /52 gradually: level B -- from the age of 2-3 months (the ability for synergies); level C -- by the first year (solution of problems connected with motion in space); level D -- by the age of two (the ability to connect movements into successive chains); and, finally, level E -- by the end of the second or the beginning of the third year (the ability to solve mental tasks, which is characteristic of human beings, and most important -- speech).

This problem was studied in great detail by T. S. Popova (1940), who showed the phases through which development of the motor abilities passes for a child mastering such motor functions as the simplest locomotions.

T. S. Popova established that fact that, in the course of mastering walking skills, the dynamic components of movement are enriched, a fuller use of reactive forces begins, and the movement itself becomes more complex. This development of motor abilities progresses in a manner which indicates that the higher levels are put into operation, and is one

of the most-clearly observed facts indicating the operation of these levels.

In the given case, the manner in which these levels successively (upwards) fulfill, first, the leading role and then - with the appearance of the higher levels - that of the background role, can be readily observed.

If, however, the above considerations are reviewed in the light of more modern data, one fact becomes apparent.

As we pointed out before, a characteristic of voluntary movement control is that the central nervous system executes its role through the functioning of two basic "control cycles". At first, these "cycles" in the "consciousness - assigning mechanism - programming mechanism" section, carry condensed information. Later, in the "servomechanism-receptors-synthesizing apparatus" - "internal control cycle" section, they break down into a series of smaller parallel chains which - after synthesis - again combine into larger ones, which carry the synthesized signals to the checking mechanism, where these signals are subjected to analysis for the purpose of making corrections. Thus, the principal characteristic of the "cycle" operation is the necessity for signal summation. In reality, there is only one "cycle", which, when necessary, breaks down into a series of parallel chains, because none of the assigning or programming mechanism divisions - as we showed in Chapter two - permits periphery signals from the lower transmitters to return to it without corresponding reprocessing, especially without checking. In other words, none of the mechanisms described above possesses independent reverse connections. /53

According to N. A. Bernshteyn's scheme, on the contrary - as shown in the description given above - everything is built on the internal connections which are separated for each level. But at the present time, this separation must apparently be dismissed (incidentally, it was an object of bitter criticism, which can hardly be considered as fully justified).

Actually, if we assume that there are separated chains of reverse connection, which function for each level more or less independently, then we would have to admit that each level possesses an independent checking mechanism. This is contrary to the basic principle underlying the synthesis of all afferent data and the control of movement as a single whole.

If, on the contrary, we assume that these levels are nothing but elements of the assigning and programming mechanisms (for the given movement), then everything falls into place: the scheme, which we described, for controlling voluntary movements is nothing but the reflex "cycles", with all their inherent characteristics, including purely physiological characteristics.

It thus follows that, for the "external cycle", any external factors which play the "assigning" role, according to N. A. Bernshteyn) may be the stimulants for the arc of this "cycle" (conditioned or unconditioned, depending on the origin and conditions). For the "internal cycle", the stimulants are not only the influence of the proprioceptors, but also those corrections which are worked out in the checking mechanism for movement and which are transferred to the assigning or programming mechanism to refine the course of movement (i.e., which play the role of "correcting" mechanisms). These stimulants (or, according to our terminology, the "controlling information") may participate in the formation of any chains of conditioned or unconditioned reflexes, but this will not change the movement control scheme which has been described.

It is thus clear that our movement control scheme, as well as certain aspects of the programming and assigning mechanism operation, do not contradict modern physiological concepts, but only supplement them with the most recent data.

In the writing example given above, levels C and D assumed the role of the assigning mechanism (level E does not lie within the framework of these mechanisms, but is rather a part of the higher conscious activity). Levels B and A assumed the role of the programming mechanism, because the former solved problems in a differentiating manner which were connected with the mental and spatial portion of movement, and the latter gave concrete expression to movement in the synergetic and other elements.

Similar forms for the operation of these mechanisms may be observed,^{/54} for example, in many other movements. Therefore, we see no reason for rejecting the assumed hypothesis, and even accept it as a working hypothesis for further studies, designating the assigning and programming mechanism of a certain movement by the levels. The fact should be taken into account that their role may depend on the degree to which the skill is automated and the problems confronting the movement. The less the degree of automation of the latter, the more frequent and extensive is the operation of the higher levels, under conditions when the lower levels are unprepared for it. Vice-versa, the greater the extent to which the biochemical aspect of movement is mastered by the lower levels, the easier and more correct the finest mental elements of movement will be resolved by the higher levels, i.e., the goals of the movement will be fulfilled.

To conclude our review, we would like to discuss P. K. Anokhin's views on the subject.

In regarding the reflex activity of a living organism as a whole (i.e., somewhat broader than N. A. Bernshteyn, who limits his scheme to the more narrow framework of voluntary movements), P. K. Anokhin ascribes the leading role to the cyclic character of reflex control, assuming that no control of reflexes (and, consequently, of voluntary movements) is possible without the existence of a cyclic system. The purpose of the latter, however, is to obtain a certain useful effect: "Every functional

system, mechanical or living, which is created for a useful purpose, invariably has cyclic character, and cannot exist without receiving reverse signalization regarding the usefulness of the effect produced." (Anokhin, 1957.)

Considering the cyclic character of reflex control in phylogenesis, P. K. Anokhin makes a special note of the fact that physiology - in dealing with functional systems over a period of many centuries - did not discover the true meaning of cyclic relationships, that the reflex theory of Descartes - which concludes the study of reflexes with only their reciprocal action - agitated it, and that the latter "due to its nature could contribute nothing to an evaluation of the results produced by a completed action". It can be readily seen that, in this case, the views of Anokhin and Bernshteyn fully coincide.

The accomplishment of a useful effect, produced by cyclic reflex control, is related, according to P. K. Anokhin, to a complex system of afferentations; the latter can be divided into three main groups:

(a) "starting afferentation", represented by the direct action of the conditional stimulant;

(b) "conditional afferentation", represented by the combination of stimuli which create a definite, dominant state in an animal;

(c) "reverse afferentation", connected with a whole complex of 55 proprioceptorial perceptions, which are required to control the operation of the muscular periphery.

However, and this is very important, "...all stimulants of the external and internal world inevitably have to pass through the stage of afferentation synthesis. The physiological meaning of emphasizing this stage is that no reflex action can be formed in the effector organs until the synthesis of all afferent influences which act upon the organism at a given moment is completed". (Anokhin, 1957.)

This afferent synthesis of the first two kinds of afferentations ("starting" and conditional") determines the conditioned reflex reaction to the combined stimulant. Moreover, the exclusion of even one afferent system immediately destroys the reflex.

Thus, it can be readily seen that the position of Anokhin does not exclude that which we call the operation of the "assigning mechanism" and of the entire remaining portion of the external cycle for movement control. In this case, afferent synthesis may mean the programming of the mental part of movement. Besides, according to P. K. Anokhin: "The removal of the frontal brain portions disturbs this afferent synthesis, and the conditional stimulants become the starting stimulants, completely disintegrating the animal reactions". (Anokhin, 1957.) Thus, as we have indicated previously, the movement loses the mental portion,

although the individual coordinations may possibly not be disturbed, since their program exists, and the lower portions of the central nervous system controlling these coordinations remain unchanged.

Upon completion of the described afferent synthesis or, according to our terminology, after the basis is laid for the movement program, a special mechanism takes over, to which P. K. Anokhin also attaches unusual importance: "However," he writes (1957), "this (the synthesis - L. Ch.) is not all ... Exactly at the moment when the synthesis of all afferent stimulations is concluded, and when the formation of the effector portion of the corresponding reflex action begins, a special mechanism is formed which we have designated the action acceptor... This mechanism is formed before the conditioned reflex itself is formed... Accepting in the form of reverse afferentation all afferent stimuli which arise as a result of the action, the action acceptor mechanism compares the results of the afferent synthesis with the results of the action produced. Thus, conformity between these stimuli completes the entire cyclic process, whereas their non-conformity results in a whole series of new reactions which must eventually produce a reflex response corresponding to the character of the acceptor action". /56

It follows from the statements given above that, according to P. K. Anokhin, the entire meaning of the cycle control lies in the fact that there must be a mechanism which, based on the proprioceptor informations, compares the reflex programming with the course of its actual execution and, if required, makes necessary corrections in the activity of the muscular periphery. It is exactly in this way that the useful effect of reverse afferentation is carried out.

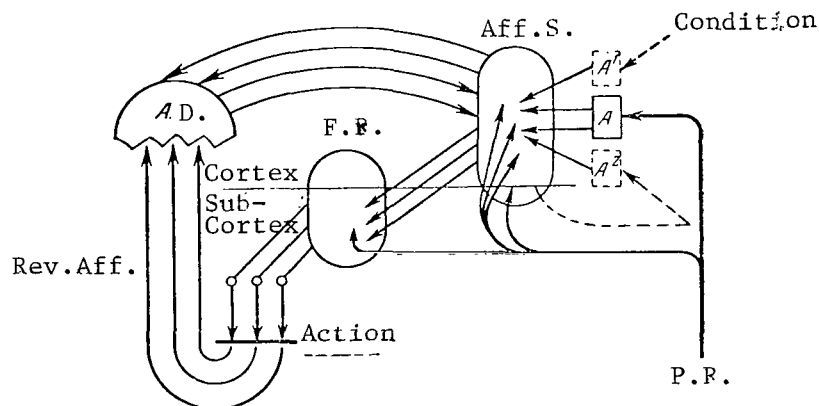


FIGURE 10

Scheme of Information Flow Under Reflex Control (According to Anokhin)

A, A¹, A² - Conditional Afferentation; Aff. S. - Afferent Synthesis; F. R. - Formation of Reflex Reaction; A. D. - Action Acceptor; Rev. Aff. - Reverse Afferentation; P. R. - Starting Stimulus; F. R. - Formation of Reflex Action.

In accordance with above statements, P. K. Anokhin shows an approximate scheme of reflex control (Figure 10), in which he distinguishes the following mechanisms: afferent synthesis (connected with both the external and the internal analyzers which feed the stimuli which characterize the conditions, etc.), the formation of the reflex reaction (here the activity of sub-cortex centers is given the appropriate recognition), reverse afferentation (this designates proprioceptors), and action acceptor (connected by a two-way connection with the mechanism of afferent synthesis). The flow of information according to this scheme is approximately as follows. The afferent synthesis organ, after receiving a certain stimulus from the external receptors and adapting it to the condition of the muscular periphery, excites the corresponding nerve centers (basically, sub-cortex centers, according to the scheme), which control certain muscular groups. Thus, nerve centers are excited /57 in the organ for the formation of reflex reaction, and this agrees with the results of total afferent synthesis. Simultaneously, the synthesis data are fed to the action acceptor which, correlating them with the information passing through the reverse afferentation from the proprioceptors, checks the actual parameters of the course followed by the reflex with the assigned parameters and, if necessary, makes the required corrections. This completes the reflex control cycle.

Let us sum up. As we already mentioned before, there are no disagreements between the P. A. Anokhin and the N. A. Bernshteyn data with respect to the principle of cyclicity in movement control. Neither is there disagreement on another very important principle - the existence of an organ which is necessary for producing the useful effect of reverse connection. Since our entire scheme of movement control is also based on these principles, it can be readily seen that our considerations do not disagree with the data of P. K. Anokhin. The situation is somewhat different in regard to the problem of the assigning and programming mechanism operation. As follows from everything discussed above, P. K. Anokhin admits, in fact, the existence of these mechanisms (the afferent synthesis mechanism approximately corresponds to our assigning mechanism, and the mechanism for formation of reflex reaction corresponds to the programming mechanism), but does not distinguish between independent, separate cycles for movement control as a whole (external and internal). At the same time, the existence of the "external cycle control" of movements (if not the reflexes, in general) cannot be denied (if only considering the tests by Krushinskiy cited above). But since the operation of the "internal cycle", and the existence therein of a special mechanism for checking assigned movement parameters with the actual parameters, was proved by P. K. Anokhin fairly convincingly, it must be admitted that the difference between our considerations and those of P. K. Anokhin consists (besides terminology) only in the fact that, in our opinion, the flow of information through the reverse connection must be divided into two independent paths. One of them corrects the mental part of movement through the external afferentation, and the other corrects the operation of explicit muscle synergies through the internal afferentation. This results in the division of the movement

control into two "cycles", which possess independent afferentation, with all the mechanisms required for this (including checking mechanisms), but does not change anything in principle. Besides, the fact must be taken into account that we are considering not the reflex activity as a whole (as does P. K. Anokhin), but the narrower problem of voluntary movement coordination, where a distinction must be made between the "control cycles", in our opinion. Thus, even P. K. Anokhin's views have convinced us of the correctness of the selected working hypothesis.

PROBLEM OF THE CHECKING MECHANISM OPERATION

/58

Out of all the remaining units of the described system, we feel it is necessary to discuss the operation of the checking mechanism of the internal reverse connection. First, let us consider the mathematical basis for the correction introduced into the course of movement by the checking mechanism.

We mentioned previously that, according to modern theories, the relation between the muscular tension and the position of the section in space must be expressed by a differential equation of the second order.

At the same time, this problem acquires an entirely new meaning in light of the study on general rules for the coordination of voluntary movements in man and higher animals. Actually, if we assume that the basic function of the movement control organs is not only the production and realization of a program for successive excitation of corresponding nerve centers and the muscular fibers related to them, but also the introduction into the program's course of the necessary correcting signals - which are produced in certain ganglions in response to the checking of the program with the peripheral information with respect to the actual parameters of the movement in process - then it must be admitted that the production of these corrections must take place not only under the conditions of definite rules, but as the result of everything occurring on the periphery as well. In other words, the mechanico-mathematical laws on which, naturally, any movement is based, must also be taken into account in the operation of the central organs. It can be readily seen that the discovery of ways and methods to utilize these laws makes it possible to penetrate the very essence of the principles underlying the central control of movements in man and higher animals.

It follows from the above that, since - in carrying out any movement - man interacts with external forces (primarily, with the force of gravity) through internal tractive muscle force, the rule underlying the process of movement coordination must be sought - apart from everything else - in the interrelationship between the muscular tension and the resulting movement.

Man can influence tractive muscle force only in one way, i.e., by varying the magnitude of muscular tension - by varying the length of muscles. Therefore, an explicit, basic criterion for the given evaluation of the operation of the organs controlling the movement must be the parameters of the latter.

However, since the muscle length and the rate of its change may be regarded, in the long run, as the function of change in the joint angles, this can be expressed through the following general relationship:

$$F_m = F \left(E, \alpha, \frac{dx}{dt} \right),$$

where F_m is the muscle tension (the moment of the respective joint); 59
 E is the physiological excitation of the muscle; α is the joint angle; t time required to execute the movement.

In the actual bone-muscular apparatus, the relationship between the lengths of muscles and values for the joint angles are so complex that the equations describing the activity of these muscles do not lend themselves as yet to accurate solutions.

However, as long as it is important for us to throw light upon the principal side of the problem, and we are not seeking explicit solutions, let us consider the most simplified example which would enable us, however, to illustrate the relationships which, in our opinion, possess the greatest significance for an evaluation of the central mechanism operation which controls movement. It is thus important to trace the manner in which muscular tension and the resulting movement interact in the peripheral cycle and how it is reflected in the operation of ganglions producing the corresponding corrections (the central cycle of interaction).

For the sake of simplicity, let us assume that

$$\Delta l = \frac{1}{E} P, \quad (1)$$

where Δl is the magnitude of muscular extension; P is the magnitude of its muscular tension (all other conditions remaining the same); E is the degree of physiological excitation of the muscle.

Let us now consider a simple example of the movement in a single joint, which, nevertheless, will demonstrate the methods by which the corresponding rules are clarified.

Let us visualize (Figure 11, I) a fixed, vertical section connected by a hinge joint to another section which freely rotates in a vertical plane. The sections are connected with a muscle of specific length, which is fixed to the movable section at a certain distance. The angle between the links may be measured.

In the given example, where it is assumed that the muscle has no antagonist and is free of internal friction, only one external force acts on the section - namely, weight; the differential equation for the movement of the section can be presented in a general form (according to the D'Alembert equation) as follows:

$$F_m + I \frac{d^2\alpha}{dt^2} + F_p = 0, \quad (2)$$

where F_m is the moment of tension of the muscle; F_p is the moment of weight of the section; α is the joint angle; t is the action time of the forces; I is the moment of inertia for the section.

But the moment of weight F_p can be expressed (Figure 1) as follows:

$$F_p = mgr \sin \alpha \quad (3)$$

or, substituting the moment of inertia I , as follows: /60

$$F_p = I \frac{g}{r} \sin \alpha, \quad (4)$$

assuming that the section has mass m , weight mg , and its moment of inertia I relative to the joint and equal to mr^2 (where $m = I/r^2$). When introduced into equation (3), it is transformed into equation (4), where r is the distance from the center of gravity of the movable section to its pivotal axis.

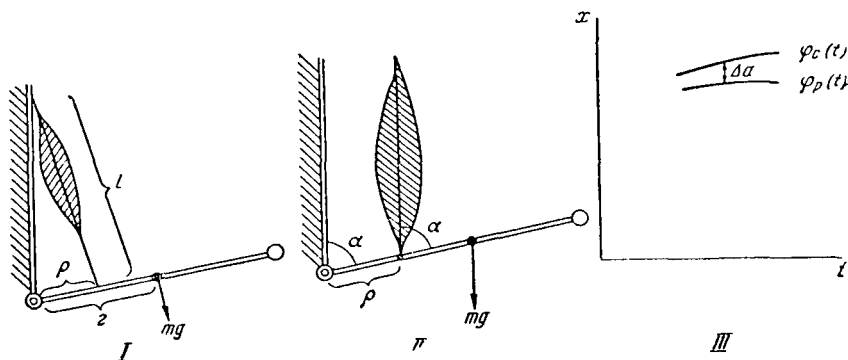


FIGURE 11

Relationships Between Muscular Exertion and the Resulting Movement Under Conditions of Maximum Simplification.
Explanation is in the Text.

The moment of muscle tension of the muscle F_m is the product of its linear tension by the moment arm of action. The first value in our example, according to the equation (1), depends on the muscle length (more accurately, on the difference between the existing length and its

length at rest), and on the mechanical degree of excitation E . Since the existing muscle length and the moment arm of its action are the functions of the joint angle, we can assume that:

$$F_m = Ef(\alpha). \quad (5)$$

The differential equation (2) after simple transformations acquires the final form

$$Ef(\alpha) + I \left(\frac{d^2\alpha}{dt^2} + \frac{g}{r} \sin \alpha \right) = 0. \quad (6)$$

Depending on the conditions (particularly, on the value of the angle in some phase of movement), it can be solved.

For us, however, it is more important to note something else - the basic variable, the angle α , and its second derivative $d^2\alpha/dt^2$ (the angular acceleration) have a cyclic interrelationship: the angular acceleration depends on the first member which is a function of angle α , and the acceleration, naturally, changes the angle itself.

If it is assumed that the value E (the physiological excitation /61 of the muscle) is constant - i.e., actually excludes the interference of the central nervous system - we would have a typical case of interrelationship according to a differential equation of second order. As is known, this case has an infinite number of solutions, and the selection of one actual solution requires the knowledge of two constants, which express the initial conditions of the given process.

Only one conclusion can thus be drawn: the central nervous system "solves" similar equations through such "substitution", in one way or the other, and, by its "interference" (by changing the magnitude of the physiological excitation of the muscle E) determines the course of the voluntary movement. Thus, both constants - the initial values - are determined on the basis of the peripheral information, preceding the commencement of movement, and the value of the variables is determined on the basis of the information obtained in the course of the movement. Since both the physiological stimulation and the value of the angle in this case are the variables which are included in both members of the equation, a simultaneous synthesis of both quantities of information seems to be necessary for the solution of the equation. Anatomically, it may be easily proved by the existence of proprioceptor formations both in muscles (the information on muscle tension), and in tendons and bursae (the information on the magnitude of the joint angle). Physiologically, the described process may be described as the formation of a conditioned reflex, where the stimulants are the proprioceptor signals regarding muscular tension and the magnitude of the angle, respectively.

Any deviation from the initial value of the stimulant (which occurs during the reflex development) becomes, in its turn, a new stimulant

leading to corresponding corrections for the course of movement.

Finally, biochemically this is proved by the physical expediency of the coordination structure elements, which is always present in movements. Actually, only by the autonomic operation of the internal "cycle", which independently "solves" the equations of movements, can one explain all those structural characteristics which are absolutely necessary from the biochemical standpoint, but which are not consciously realized by man in the execution of automated skills.

Let us give one more example. For this purpose, we shall make the form of the first member of equation (6) more concrete, performing one non-fundamental simplification: let us assume that the muscle (Figure 11, II) remains parallel to the first section, never changing the direction of its longitudinal axis - i.e., always forming angle α which equals the joint angle, with the movable section. In this case, the moment arm of action for the muscle is:

$$\rho \sin \alpha, \quad (7)$$

and the tension, as shown above, is expressed as the product of the /62 mechanical degree of excitation (E) by the difference between the muscle's length and its length while at rest, as follows:

$$E (l_0 - \rho \cos \alpha), \quad (8)$$

where ρ is the distance from the point at which the muscle is connected to the movable section to the center of the joint, and l is the muscle length.

After this, equation (6) acquires the following form:

$$[E (l_0 - \rho \cos \alpha) \cdot (\rho \sin \alpha)] + I \left(\frac{d^2 \alpha}{dt^2} + \frac{g}{r} \sin \alpha \right) = 0, \quad (9)$$

which makes it possible to find an explicit solution for this case.

Let us assume now that the initial conditions of this equation are determined and, consequently, the peripheral cycle, which it expresses, is known. Let us determine the manner in which the second equation must be formulated; this equation will illustrate the manner in which the correction in the central cycle of interaction is determined.

Let us assume that the solution of equation (9) leads to an explicit expression for variations of the joint angle in time:

$$\alpha = \varphi_p(t).$$

However, the program for the operation of the internal cycle, controlling the given movement, requires that, at a given moment of time t , this

angle has the following value:

$$\alpha = \varphi_c(t).$$

The task and function of the checking mechanisms of this cycle is to compare at each moment the assigned value $\varphi_p(t)$ with the actual value which is reported from the periphery $\varphi_c(t)$, thus determining the most important index - namely, the difference between the two:

$$\Delta\alpha = \varphi_p(t) - \varphi_c(t).$$

In the concrete example of equation (9), the positive sign before the value of this difference $+\Delta\alpha$ (Figure 11, III) means that the angle α is greater than that required by the program - i.e., the muscular tractive force lags behind, and the degree of its excitation must be increased. As a result, in response to the signal $+\Delta\alpha$ from the checking mechanism, the corresponding sections of the central nervous system work out a correcting command $+\Delta E$, thus increasing the degree of excitation, and, consequently, the muscular tractive force. On the other hand, the signal $-\Delta\alpha$ results in the command $-\Delta E$. In other words, the signs of $\Delta\alpha$ and ΔE coincide, and the value of ΔE depends on $\Delta\alpha$.

In a general form, this relationship may be expressed as $\Delta E = \varphi(\Delta\alpha)$, provided that $\frac{dE}{dt} > 0$.

The above example is a general expression for the central cycle of /63 interaction between muscular tension and the resulting movement, as applied to the given example. Ordinarily, this relationship is more complex: on the basis of data sent from the receptor transmitters, the central nervous system checks not only the angles, but also their first and second time derivatives as well. In this case, we have:

$$\Delta E = \varphi\left(\Delta\alpha, \Delta \frac{dx}{dt}, \Delta \frac{d^2\alpha}{dt^2}\right).$$

But these are not the principal complications.

The above examples indicate only the mathematical methods for establishing the operation of the central organs which control the extremity motion of man and higher animals. For the purpose of formulating the actual equations describing even a simple flexion in a single joint, it would be necessary, in addition to the above data, to take the fact into account that nearly every muscle has an antagonist; any one of them has (the same as any joint) internal friction. The fact that the magnitude of muscular tension, the physiological excitation, and the muscle length are not connected by a direct relationship must also be taken into account, as well as the fact that the variation in the muscle parameters may lead to a change in the angle between the

muscle and the section. We are not even mentioning the fact that the extremities of man and animals represent multi-sectioned kinematic chains which are mostly open in the course of movement. During the movement of these chains, very rarely one single section remains stationary. This results in the formation of reactive forces, and their consideration will naturally lead to further complications in the equations.

It follows from the statements given above that the development of equations for voluntary movements is a very difficult problem, which at the present time is insoluble. Therefore, we believe that studies in the field of the checking mechanism operation must be directed towards a study of the correction signal.

For artificial systems, this problem is successfully solved by the theory of automatic control, by the theory of servomechanisms in particular (Neiman, 1958). The enormous complexity of the living organisms makes it necessary to renounce this path for the time being, and to seek new methods in an investigation of external phenomena showing the checking mechanism operation.

Therefore, let us consider the checking mechanism operation from a somewhat different angle.

To solve the given problems, this mechanism must possess information on the coordinates of the extremity sections and on their first and second derivatives (rate and acceleration).

In N. A. Bernshteyn's (1957) opinion, the proprioception, supplying this information in the form of changes in the joint angles, is sensitive only to the position of the sections, and has no direct transmitters /64 for rate and acceleration. The reason for this is the structure of receptors and their physiological properties, which we described in the first chapter. Therefore, on the basis of the general scheme for movement control, it is possible to assume that information on rate and acceleration of a certain section can be produced only in the checking mechanism. For this purpose, as always in an analysis of the rate of coordinate change, their first and second differences may be used. In other words, the signals sent by the transmitters at a given moment of time are compared with their values observed shortly before this moment. On the basis of this comparison, the rate of movement is received, and (by repeating the comparison process) the acceleration of the section or extremity is also received.

According to N. A. Bernshteyn's data (1957), these comparisons occur every 0.07 - 0.12 seconds. These numbers are not random, and indicate the discrimination in the operation of both the checking mechanism and the entire nervous system as a whole. These numbers unexpectedly remind us of the nature of the "foot" acceleration in bicycle pedalling, which we established. In the study of these accelerations, it was established that in bicycle riding, even the most qualified racer (for

example, the Olympian champion, V. Kapitonov) does not exert action on the pedal in one single effort, without interruptions during the entire cycle. On the contrary, it was established that this effort has an impulsive, distinct character, in which the positive accelerations of the foot alternate during the cycle with negative accelerations, not less than 14-16 times a second.

In Figure 12, we show the change in these accelerations, indicating by vectors those which, having a positive value, create the actual bicycle motion.

A similar phenomenon was observed by V. S. Gurfinkel' (1955) in the movement of a loaded and unloaded arm, always vibrating with the same frequency. In all cases, apparently, a smooth course of movement was not observed, but, on the contrary, the alternation of accelerations and interruptions between them, and the alternations always occurred at the frequency of 8-16 cycles per second (i.e., with the interval of 0.07 - 0.12 seconds). Although this problem, undoubtedly, requires further detailed study, it can be assumed, on the basis of the above information, with a certain degree of probability that some functions of the checking mechanism must be connected with the given time parameter - namely, the frequency of 8 - 16 cycles per second determines the checking frequency for determining rates and accelerations of the moving section.

The checking mechanism must, in our opinion, not only determine the correction of the movement at the given moment, but - based on the total mental task of the movement received from the assigning mechanism - it must also "predict" the course of movement in future moments. /65

It is very apparent that without this the execution of a whole series of sport or work movements would be impossible. However, the problem of "predicting" the course of movement and introducing corrections, so to say, in advance has not been studied at all at present.

As for the general principles underlying the operation of the checking mechanism, it is necessary once again to emphasize the enormous stability of this operation. It is quite possible that this mechanism, as well as the entire control system of voluntary movements, possesses - in addition to the basic arc of reverse connection - a great number of local reverse connections, and also parallel, compensating small arcs and chains.

A significant role in ensuring stability of movement, according to the general theory of self-regulated mechanisms, is played by the presence in the organism of such reverse connection, due to which the checking mechanism reacts not only to the difference between the actual and required course of movement, but also to the rate of change in this difference. In Wagner's opinion (R. Wagner, 1954), the compensation for insignificant deviations, approaching the threshold deviations, is carried out according to this principle. However, all of these problems related to

movement control have still been studied to the smallest extent.

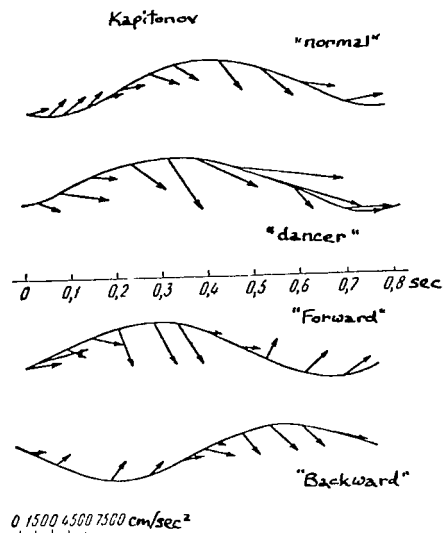


Figure 12

Trajectory of the Pedal Axis Displacement in Bicycle Riding with Various Methods of Pedalling ("Dancer") and with Various Ways of Sitting ("Forward", "Backward", and "Normal") by a High-Class Bicyclist-Sportsman.

Original.

CONCLUSIONS

We have discussed in the most general way the basic scheme for the coordination of voluntary movements in man (as it appears at the present level of knowledge).

This scheme is hypothetical to some extent, but it accomplishes to a certain degree its function as a guide. We must now sum up the results which, we believe, can be presented in the form of conclusions. /66

1. Voluntary movements in man and higher animals may be considered only as a complex cyclic process.
2. The process consists of two basic cycles: external, based on external afferentation, and internal - based on internal afferentation.
3. In performing the mastered skills, the external cycle is connected with conscious activity, and the internal is connected with the operation of muscular synergies.

4. Both afferent paths together and separately may be included in the reflex arcs, with various physiological values, as both conditional and unconditional paths.

5. Taking into account the number of degrees of freedom of open kinematic chains - which do not lend themselves to exact determination and which compose the extremities of man and animals - the complexity of the force field of movement, the disparity in the relation between muscular tension and the resulting exertion, and also the necessity of producing a dynamically stable movement, one can safely say that the coordination of voluntary movements - which primarily requires the transformation of the muscular periphery into a controllable system - is a reflex entailing the obligatory participation of the self-regulating control mechanism.

6. The most important, inherent part of the entire movement control is the internal reverse connection, whose receiving elements can be regarded as the muscular and tendinous receptors, "transmitters", which send signals on the state of the muscles and the position of a section in space.

7. The signals from these transmitters after synthesis must be included in the most important element of the entire system, the checking mechanism, which essentially determines the basic task connected with performing the coordinated movement - the establishment of an interrelationship between muscular tension and the resulting movement. The checking mechanism, apparently, is located in the cerebellum.

8. On the basis of the complex interrelationship between the checking mechanism, the assigning element, and the motor memory, the necessary corrections are produced which, entering again into the programming mechanism, continue to control the corrected movement. On the basis of certain indirect data, it can be assumed apparently that the average frequency at which such corrections are introduced generally varies for the automated skills within the range of 8 - 16 cycles per second.

9. The course of an unmastered motor skill can be regarded as control under conditions when the internal cycle is unprepared for the execution of its functions. In the majority of cases, this leads to biochemically-imperfect movements, because the explicit synergetic elements remain primarily outside of the control, or are controlled by the external cycle, whose receptors cannot perform the most important action - establish the correct interrelationship between the muscular tension and the resulting movement. As a result, the mental part of the movement cannot be fully and correctly realized.

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10. The course of the mastered skill, on the contrary, may be regarded as control both with respect to the external cycle (the mental part of the movement) and the internal cycle (automated elements of movement). The latter, in this case, must work out and control the most convenient forms of the direct (in elements) realization of the skill. Because this ensures the biochemical appropriateness of the movement, the external cycle will be able to perform the finest elements of the mental part of movement.

It can be assumed in this case that the control cycle in some segments is broken down into a series of small parallel chains, possessing a wide range of interchangeability.

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CHAPTER II

COORDINATION OF VOLUNTARY MOVEMENTS OF MAN IN AN INCREASED GRAVITATIONAL FIELD

The purpose of the investigations described in this chapter is to trace the changes in the coordination of movements in man in an increased gravitational field.

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Since the presence of man under these conditions must, according to the laws of mechanics, lead to a definite increase in body weight, we must assume that any type of overloading (for example, in the centrifuge) will adequately reproduce both the physical and the physiological state of man in analogous (increased) gravitational fields. This makes it possible to simulate the particular state depending on the conditions of the experiment, and at the same time to regard the observations as being made under conditions of a gravitational field having the corresponding magnitude.

At the same time, a whole series of investigations which have been conducted before ours indicate that, under conditions of overload caused by certain accelerations, the coordination of movements in man (as many of his other functions) must undergo some changes.

Z. Geratevol (1956) in a detailed investigation devoted to psychology of man in flight, analyzing the question of coordination of movements under overload conditions, said: "The movement of an extremity and the state of motoricity, in relation to movements under the influence of accelerations, undergo considerable changes. The effects of accelerations in the direction of the head consist of the activation of a group of muscles taking part in the control movements. The effect of accelerations on the movements is most pronounced in relation to small forces (from 4 to 9 kg) and least pronounced in the operation of controls (of an airplane - L. Ch.) with 18 to 23 kg of force."

The opinion of the Soviet investigators in regard to this question (Usachev, 1961) is that the described phenomenon is caused by the fact that, under conditions of overload, the contrast provided by the force of the hand on the skin surface of the wrist is hidden by the sensation of a hand which has increased in weight.

This allows us to assume that in this case the disturbances in movement coordination are caused, in addition to everything else, by the complication of the checking mechanism operation of the internal movement control cycle. This takes place because the sharp change in the control information, caused by an increase in the acti-

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vity of the muscular groups performing the skill, disturbs all of the basic work parameters of these mechanism, which are established in mastering the skill. As was indicated in the first chapter, the coordinated accomplishment of movement depends on the stability of the internal cycle.

That is why our problem can be reduced to investigating the effect of overload on the activity of the "internal cycle". Consequently, it was necessary to select a movement whose control could be most completely shifted to the particular "cycle". It was also necessary to establish a clear mathematical estimate of the possible coordination disturbances of the selected skill, in a way which would make it possible to compile material which would enable us to determine the statistical authenticity of the obtained conclusions. It was also necessary to take the fact into consideration that, under the conditions of overload, the movement of body sections becomes difficult, and for this reason the skill should not include any sharp movements of the extremities.

The magnitude of the overload could fluctuate within the limits permitted by endurance (and this, as we know, amounts to 8-10 tolerance units or 9-11 g), but in all cases it should follow a direction which would not disturb the blood supply to the brain. Otherwise, the latter itself could disturb the movement coordination, independently of distortion of the peripheral information.

This is explained by the fact that - as was indicated by numerous observations both of foreign and Soviet investigators (Strel'tsov, 1938, Bondura and others, 1960; Usachev, 1961) - the accelerations in the head-pelvis direction cause the outflow of blood from the head, and lead to considerable disturbances of the brain activity. On the other hand, accelerations in the chest-back direction (lateral overload) can be tolerated much more readily by man, and the blood supply of the central organs if disturbed can be tolerated only to a considerably lesser degree. Therefore, movement coordination disturbances, which are observed in these overloads, could be explained by the basic distortion of the central information.

After a number of trial observations, we selected the following method.

METHOD

The experiment was conducted on clinically healthy adults of the male sex.

The subject, under certain overload conditions must apply

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proportional pressure with a finger against a hard support. Differentiation of the presses had to be done in such a way that, if the first press of each pair amounted to x kg, then the subject tried to make the second one $0.5 x$ kg. In the course of each observation, the subject had to complete not less than 50 pairs of such proportional presses, spending about one second on each press.

We selected the described skill due to the fact that, since muscular coordination is reduced, in the final analysis, to a correct proportioning of the single muscular forces, any disturbances must first of all be expressed in a distortion of these proportions, and this can be detected simply and readily in the ability of the subject to regulate efforts which follow one another.

In addition, this differentiation of efforts greatly facilitated the mathematical evaluation of the coordinated execution of the given skill. The latter resulted in a calculation of the conditional value, which we called "the index of force differentiation" (F), which was determined as the ratio of the difference between the large and small forces, which follow each other, to the magnitude of the small force.

It can be readily seen that, if the subject strictly observed the conditions of the force differentiation, then F was equal to 1. Since the ratio between the efforts was equal 2:1, then:

$$\left(x - \frac{x}{2}\right) : \frac{x}{2} = 1.$$

However, if during the execution of the second (in each pair) press, the subject made it stronger than $0.5 x$, then F proportionately decreased, and in the equation of forces was equal to zero.

If the second effort was smaller than $0.5 x$, then this also worsened the index of force differentiation, since in this case it was calculated according to a slightly different equation:

$$F = \frac{x - \frac{(x-y)}{2}}{x-y},$$

where x is the value of the first force, and y -- of the second.

In other words, an identical increase or decrease of the second press above the value (0.5 of the first) equally indicated a similar deterioration in differentiation of these forces.

Before the beginning of the basic observations, all of the subjects (adult, normal males, who after a special medical examination were permitted to endure overloads) went through prolonged training to develop the skill of force differentiation.

The training was arranged in such a way that only the first attempts to differentiate forces according to the assignment were completed by

the future test subjects with visual control (based on deflection of arrows on the instruments recording the magnitude of the press force). Then the latter was excluded, and all of the remaining training sessions were conducted in such a way that the subject evaluated force differentiation by relying only on the "muscular sensation". However, the control over the quality with which the movement was performed was left to the experimenter. /73



FIGURE 13

Tensometric Recorder, used for Studying
the Magnitude of Pressure Forces.

In this way, the external control cycle of the particular movement was excluded from its control to a maximum degree, and - as follows from all statements given in the first chapter - transferred to the internal cycle. It can be readily seen that this was one of the most important purposes of the training.

The first experimental attempts to differentiate forces, according to the necessary parameters, indicated that the average man, after completing several tens of these presses, could not bring F to one. As a rule, this coefficient was at the best 0.7, and usually considerably less. It was necessary to perform not less than 150 - 200 minutes of actual training of each subject in order to bring F to 0.85 - 0.90.

After this, basic observations were made on the execution of a mastered motor skill by all of the subjects, while rotating in a centrifugal chair, with the following overload parameters:

Rapidly-occurring stable overloads for 2 minutes at 3 and 7 tolerance units.

An overload, increasing during the period of 2 minutes, from 0 - 7,

and in some cases up to 8 tolerance units.

In the observations of the first two series, 20 to 30 seconds were used for the centrifugal run, and in the third series each unit of overload was maintained for a period of 20 seconds.

The direction of the overload was back -- chest (lateral).

The values of each press force were measured by the usual tensometric method. The presses were executed with the index finger (in single experiments, with the thumb) of the right hand of the subject, on a hard ring, to which a recorder was attached which indicated the press parameters (Figure 13). Subsequently, these signals were transmitted to an amplifier and a recording device (oscillograph). Samples of actual recordings are shown on Figure 14. /74

In the course of some observations, the bioelectric potentials from the brachioradial muscle (m. flexorcarpi radialis) were also recorded. These recordings were for the purpose of tracing the character of changes in the operation of the leading muscular groups, which were executing the given skill -- that is, for establishing any possible distortion of the control information.

In addition, with the special purpose of discovering the possibility of decreasing the blood supply of the brain during overloads, the arterial pressure was taken in the helix of the subjects, and in some cases, for the control of their general state, electrocardiograms were recorded. The respiration and pulse rate were recorded.

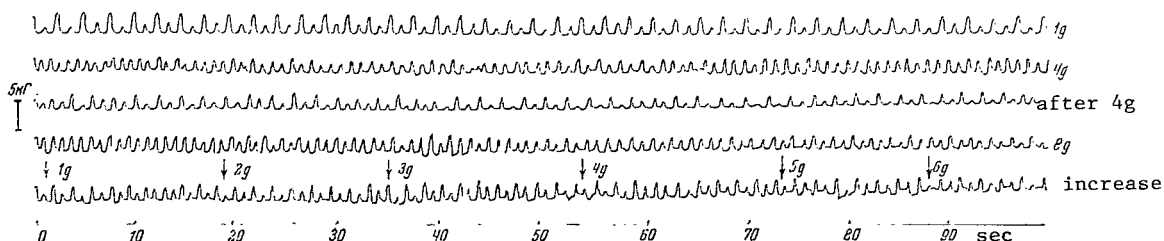


FIGURE 14

Samples of Recordings on the Execution of Differentiated Presses of Fingers Against a Solid Support, Under Normal and Increased Gravitational Fields. In Each Pair, the High Peak is the First (Strong) Press; the Lower -- Second, Which is Differentiated From it.

Before each skill was performed under the overload condition, not less than 50 pairs of presses were recorded to determine the quality of the skill in a normal field ("background"). Analogous recordings were conducted also after the effect of the overloads ("aftereffect").

The experiments were conducted on four subjects, who - under the conditions mentioned above - completed, in the course of 30 observations, not less than two thousand pairs of presses.

All of the collected material was subjected to varied statistical processing, and the reliability of the obtained mean values was determined with existing methods. The processing of the material was reduced to determining the mean values of the presses, their quadratic deviations, the calculation of the index of force differentiation (F) - both as a whole, and in twenty-second periods of each observation - and the calculation of the coefficients of correlation and regression, as well as the extent of error, according to the generally accepted rules. /75

INVESTIGATION RESULTS

Our observations indicated that, under the influence of overloads, the coordination of the execution of the investigated skill changes. These changes were found to be far from random and, as a whole, subject to specific rules. These rules can be observed with sufficient clarity only in an analysis of the general mean values, when the effect of random deviations, which are caused by individual peculiarities of the subjects (the so-called "scattering of data") can be reduced to a minimum. The summary of these values is shown in Table 2.

Let us begin the analysis of Table 2 with the mean force values, which, as is seen from the error limits, are completely reliable. An examination of these data shows that the value of the first (large) force, under the influence of overloads, changes comparatively little (from 5300 to 5400 g). We are inclined to explain this situation by the fact that the subjects not only were sufficiently prepared to accurately monitor the force, but that it was executed within a specific limit. This is substantiated by the value of the mean quadratic deviations of these forces, which in all cases of overloads differed to a comparatively small extent from the dimensionality which was apparent during the execution of the skill in the normal field.

The situation was quite different in the case of the second pressing force - which was differentiated from the first. Here an opposite phenomenon was observed: if, in the execution of a skill without any overload, all of the subjects executed this press with an average magnitude of about 2500 g, which made it possible for them to reduce the index of force differentiation, on the average, to 0.83, then during

an overload of 3 tolerance units this quantity increased up to 3290 g (that is, it increased by 31.6%). During an overload of 7 tolerance units, it increased up to 3383 g (that is, it increased by 35.2%). A no less distinct picture is produced by the mean quadratic deviations. In a normal field, they are on the average of ± 446 g, but during overloads they almost double. As a result, the index of force differentiation - the mathematical evaluation of the quality with which the investigated skill is executed - proportionately deteriorates. (To 0.63 during overloads of 3 tolerance units, and 0.57 for 7 tolerance units.)

In other words, an increase in the field of forces not only /76 leads to a disturbance of given movement coordination but also to the fact that this is expressed exactly by the same movement component which we have used as a basis for the investigated skill. This proves the accuracy of the selection and the evaluation of the investigated movement.

These statements can also be substantiated by the fact that the coefficient with which the second press regresses from the first - which indicates the quantitative relation between the forces, and which, consequently, must equal 0.5 in the most optimal case - during the execution of movements in a normal field, has a mean value of 0.35. Under overloads, it increases (that is, improves) almost to the norm.

The positive correlation coefficient, which is below one on the average (this indicates that the direct positive connection between forces, although not complete, still exists), during the execution of a skill with an overload of 3 tolerance units also considerably increases. Some decrease of this coefficient, during an overload of 7 tolerance /77 units (up to 0.34), in our opinion, only indicates that the more difficult conditions, under which the movement is executed, must make this connection worse. But if these conditions change little, and stimulate man rapidly, then this connection can also increase, as takes place in a field increased by a factor of three.

These statements refer to a stable field, but if we turn to the dynamics of the indicated indices in a field, which gradually increases from a normal one to an eight-fold one, then it can be readily established that here too we have coordination changes in the investigated movement, although in a somewhat different form.

Actually, if - during increasing overload - the changes in the first and second press forces and their quadratic deviations, on the average, during the whole period of acceleration do not differ, in principle, from the dynamics of analogous indices during stable overload, then the coefficient of regression and correlation is found to be much higher than in stable overloads of 7 tolerance units. This indicates that the corresponding connections between the forces - and also the ability of the subject to regulate the press forces as a whole, during increasing overloads - are higher than during similar overloads

TABLE 2
GENERAL MEAN DATA ACCORDING TO BASIC INDICES

Index	Without Overload (Background)	With Stable Overload		With Increasing Overload Up To 7 Tol. Units
		3 Tol. Units	7 Tol. Units	
Mean Force Values (M) g				
I Press	5353	5291	5408	5410
II Press	2499	3290	3383	3291
Mean Quadratic Deviations (σ) g				
I Press	<u>+516</u>	<u>+689</u>	<u>+657</u>	<u>+630</u>
II Press	<u>+446</u>	<u>+861</u>	<u>+872</u>	<u>+687</u>
Mean Error (m) g				
I Press	<u>+ 75</u>	<u>+ 98</u>	<u>+ 98</u>	<u>+ 87</u>
II Press	<u>+ 63</u>	<u>+121</u>	<u>+131</u>	<u>+102</u>
Coefficient of Cor- relation between the Press Forces...	0.40	0.50	0.34	0.45
Coefficient by which Second Force Re- gresses from the First	0.35	0.63	0.42	0.58
Index of Force Differentiation (F)				
Average during the Period of Over- load	0.83	0.63	0.57	0.60
At the Start of the Overload Effect ...	0.81	0.57	0.41	0.73
In the Middle of the Period of the Overload Effect ...	0.84	0.68	0.59	0.57
At the end of the Period of the Overload Effect ...	0.82	0.73	0.66	0.52

which are stable. This is indicated by the mean value of the differentiation force index, which during an increasing overload is also on the average somewhat higher (0.60 as against 0.57).

This can only be explained by the ability of the human organism to adapt to overloads, and consequently, to some degree, to re-establish the coordination of movements.

Since the latter has a very important significance, and evidently, has not been previously described, let us turn to the dynamics of the index of force differentiation in the execution of a skill under conditions of stable overloading.

As is indicated by Table 2, this index in the course of the execution of the investigated movement does not remain at a stable level. If during the execution of a movement in a normal field, it fluctuates within rather insignificant limits (from 0.81 to 0.84, which in addition indicates a definite stability of the movement as a skill, and permits us to use this term), then, when the particular movement is performed in an increased field (regardless of its parameters), the same picture is observed. During the first third of the overload action period, the subjects differentiate the forces much more poorly than in the second, and in the last third, further improvement of the differentiation index, which clearly tends toward a specific norm, is observed. Of course, under different overloads this index is different, but its general tendency to improve is quite clearly expressed.

In other words, the central organs regulating the particular skill do not remain indifferent to disturbances of its coordination, and begin to reorganize their activity in such a way that the leading dynamic movement components, to a more or less acceptable degree, will return to the norm. There is no doubt that this is caused by the stability of the particular skill - that is, it is the specific result of preliminary training. /78

Thus, the examination of Table 2 permits us to draw two conclusions: (1) in the execution of a movement in an increased field, the coordination of movements must in one way or another be disturbed; (2) if this skill is sufficiently stabilized and is executed in the force field which preserves its parameters, then the initial deterioration of movement coordination must be replaced by its re-establishment.

Let us now attempt to find some specific rules in the examined phenomenon. In order to do this, let us turn to Figure 15, in which the mentioned relationships are graphically illustrated. The values of the index of force differentiation (F) from 0 to one are plotted on the ordinate axis, and on the abscissa - the values of the gravitational field (that is, the acceleration of gravity) in a logarithmic scale. For purposes of convenience, the time scale was combined with the scale of accelerations, so that the abscissa of time would correspond to the abscissa of accelerations. /79

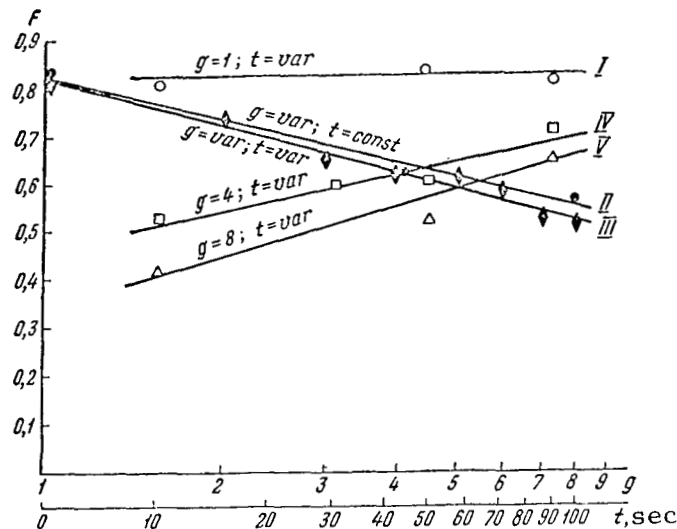


FIGURE 15

Relation Between the Index of Force Differentiation (F), Logarithms of Overload Value (g), and Time Required to Execute Presses (t) in Various Gravitational Fields. (Original.)

I - In a Normal Field; II - Average Data During Execution in a Stable (Duration of 2 Minutes) Field of 1,4,8 g; III - In an Increasing Field, for the Same Period from 1 to 8 g; IV - Changes During a Two-Minute Execution of a Skill in a Field of 4 g (Overload of 3 Tolerance Units); V - The Same in a Field of 8 g (Overload of 7 Tolerance Units). Average Data from all Observations.

The line I indicates the dependence of the index of force differentiation (F) on the duration of the execution of a skill in a normal gravitational field, that is, $F = F(t)$ for $g = 1$ (overload equals 0 tolerance units). It can be readily seen that it is practically parallel to the abscissa axis, which indicates that under normal conditions, F should not undergo any considerable fluctuations. If the subjects are adequately trained, they are able to regulate the necessary force presses with $F = 0.85$. In other words, the coordination of a particular movement in a normal field is characterized by the ability of man to correctly differentiate - within certain limits, but for quite a prolonged time - between the force of two successive presses of a

finger on a hard support.

At the same time, it can be seen from the same graph that the relation between F and the logarithm of gravity [that is, when $F = F(g)$, and $g = 1,4,8$], in the execution of a particular skill under the conditions of a rapidly-formed stable overload (line II), also satisfactorily approximates a straight line. This gives us the right to assume that the deterioration magnitude of the force differentiation (ΔF) - that is, the actual disturbance of coordination of a given movement - is determined by the equation:

$$\Delta F = \Delta y = y_0 - y,$$

where Δy is the magnitude of the change in the index of force differentiation; y_0 - its value in a normal field; y - the same, in an increased field.

In turn, Δy can be represented in the form:

$$\Delta y = \operatorname{tg} \alpha \cdot \ln x,$$

where α is the angle of inclination for a straight line toward the abscissa axis; x - magnitude of the field increase.

Since $\operatorname{tg} \alpha$ is the quantity which is constant for everyone and, as can be readily seen, depends on his condition and training, then its value can be conveniently expressed in the form of a specific coefficient K . At the same time, the magnitude of gravity acceleration is usually designated by g . Therefore, the entire equation acquires the following form:

$$\Delta F = -K \ln g. \quad (1)$$

It follows from this equation that the limits of possible disturbances of movement coordination in an increased gravitational field (if by the term, coordination, we mean the value of the leading dynamic /80 components) will depend on the condition of man in this field, and the logarithm for gravity acceleration of the given field.⁽¹⁾

We should make the reservation here that this will not at all mean a decrease in the magnitude of the dynamic components. This equation indicates only the parameter fluctuation limits of the coordinational structure, and these can be both positive and negative.

As follows from the same figure, this relation retains its force also during the execution of movements in a gradually-increasing field,

(1) It is interesting that this important relation is related to the law of Weber-Fekhner.

where $F = F(gt)$. This is evident from the fact that the changes in the index of force differentiation in an increasing field also approximate a straight line (line III).

If we continue the analysis of the graphs in Figure 15, it can be readily seen that the restoration of the dynamic indices of the movement being studied, during its systematic execution in an increased gravitational field, is subject to logarithmic dependence.

In Figure 15, lines IV and V designate the dynamics of the re-establishment of the index of force differentiation, when $F = F(t)$, and $g = \text{const}$. The first illustrates the changes in this factor during the execution of a skill in overloads of 3 tolerance units, the second - of 7 tolerance units. One argument for these lines is the time required to complete a movement, which is superimposed, as we said before, on the abscissa axis with the overload scale. As follows from these data for our observations, the relation between the logarithm for the time required to execute the skill in a stable, increased field and the index of the leading dynamic component also satisfactorily approximates a straight line. Consequently, we can assume that the parameters for re-establishment of movement coordination in this case assume the form:

$$\Delta F = + K \ln t, \quad (2)$$

where K is the coefficient, characterizing the condition and training of man in an increased gravitational field (but, evidently, it is not identical to the analogous coefficient from equation (1), in so far as man's ability to retain movement coordination can in some cases be different from the ability to re-establish it); t - time, during which the particular skill is executed; ΔF - the re-establishment magnitude of the leading dynamic components.

In addition, it is important to mention that in the observed re-establishment of the index of force differentiation factor (that is, the actual coordination of the selected skill), not only the time required for its completion, but also the magnitude of the gravitational field in which it is performed, is of significance. This is due to the fact that, as is easily seen in Figure 15, the straight line, which represents the re-establishment of this index in a field of 4 g, is higher than in a field of 8 g - that is, with a smaller increase of the gravitational field, the disturbance of the skill is less, and the re-establishment is more rapid than in larger overloads. But it does not absolutely follow from these statements that, during prolonged execution of the described movements, the quality with which the skill is executed can improve as much as is desired as a logarithmic function of the time of execution. This relation evidently retains its force only within certain (until now unexplainable) limits - for example, before the indices of the coordinational movement structure return to a specific norm, depending on the condition of man and the magnitude of gravitation. However, this norm is still unknown. Therefore, we are just

stating this fact, prior to a more detailed investigation.

Consequently, it follows from equation (2) that, during a systematic execution of a specific motor skill in an increased, but stable field of force, the initial decrease of movement coordination must be replaced by the re-establishment of the leading dynamic components of indices for this movement. The duration of this act will depend on the condition of the person in a given field, the magnitude of gravitation, and the period required to execute the skill.

Generalizing equations (1) and (2), and the approximations expressed by lines II, III, IV and V, appearing in Figure 15, it can be said that a man, situated in an increased gravitational field, at first decreases his movement coordination. Later, if the magnitude of the field does not increase, but remains at a specific, accessible level, the dynamic components will return to the specific norm, under the condition of a sufficiently-frequent execution of these movements in the particular gravitational field and with appropriate training of the person.

At the same time, these approximations indicate one other interesting situation. If we solve equations (1) and (2) in relation to K , it can be seen that in the first case $K = \frac{-\Delta F}{\lambda_{ng}}$, and in the second $K = \frac{\Delta F}{\lambda_{nt}}$. In other words, the condition and the training of a man executing the movement in increased fields of force can be evaluated first, by the degree of deterioration of the specific dynamic index for the particular movement, during its execution in a certain field. Secondly, it can be evaluated by the speed with which this index is restored during systematic accomplishment of the same skill in stable gravitation.

It can be readily seen that this reveals possibilities for an accurate control over the training process of a person who must operate under increased gravitational fields, and this control can be carried out simultaneously on the basis of two indices.

In concluding the description of the results derived from the /83 main observations, we would like to include the recording of bio-electric potentials from the leading muscular groups of the arm executing the mastered skill. As can be seen from Figure 16, where these recordings are shown, the overload always causes an increase in the bio-electric activity of these muscles. In addition, this activity is dependent on the magnitude of acceleration. This does not contradict the well-known data, obtained previously by V. I. Babushkin and others (1958). However, the fact that the bio-electric activity increases substantiates our thesis that, during the execution of movements under overload conditions, the subjects have to overcome - apart from the necessary pressing force - the greatly increased extremity weight. This makes the increase of the muscular activity necessary, and consequently distorts the information transmitted to the central organs which regulate the particular skill, with all of the described results.

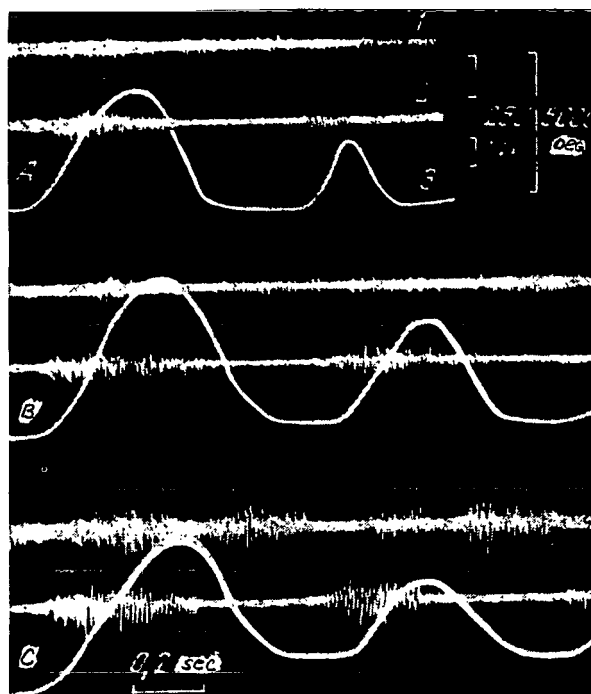


FIGURE 16

Oscillograph Recording of Two Presses of the Finger, One Following the Other, Against a Hard Support, and the Bio-electric Potentials in Muscles of the Forearm During the Execution of the Skill in a Normal Gravitational Field (A) in an Overload of 3 Tolerance Units (B) and 4 Tolerance Units (C). Original

- (1)-Biological current in the musculus brachioradialis;
- (2)-Biological current in the flexor capri radialis;
- (3)-Tensogram of pressing forces.

In addition, we must mention that both the electrocardiogram recording (Figure 17) and the data on arterial pressure in the helix of the subjects (Table 3) did not reveal any changes in the organism, which would indicate changes which are not characteristic for man under conditions of lateral overloads.

On the contrary, if only a regular pulse rate increase is indicated on the EKG (electrocardiogram), then the recording of the arterial pressure will not show a decrease in the blood supply to the higher parts of the body, but more likely, an increase of it - however, without exceeding the normal limit, which has frequently been given before us (Kotovskaya and others, 1962). Consequently, even if we consider that the method of investigating the blood volume of the brain by fixation of arterial

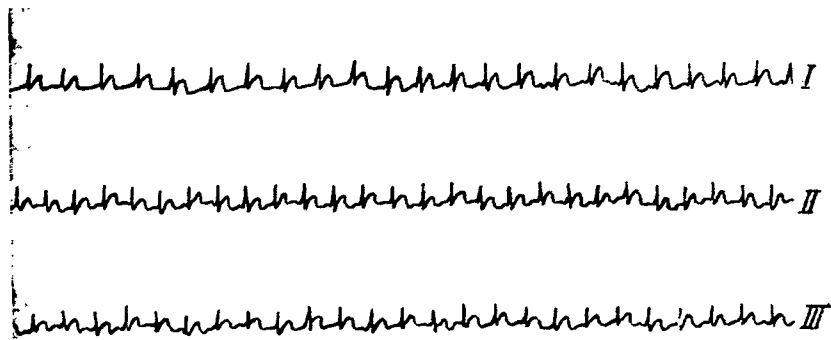


FIGURE 17

Electrocardiogram of the Subject During the Execution of the Skill in Various Gravitational Fields. Lead from 3-4 Intercostal Area Units.

I - Background; II, III During Overload of 3-4 Tolerance Units.

TABLE 3

AVERAGE DATA ON ARTERIAL PRESSURE IN THE HELIX OF THE SUBJECTS AND THE RESPIRATION FREQUENCY

Type of Action	Arterial Pressure in the Helix, mm Hg	Respiration Frequency	Pulse Rate Per Minute
Background (without Overloads).....	100	16	84
Stable Overload			
3 Tolerance Units..	130	30	96
7 Tolerance Units..	140	32	102
Increasing Overload (moment at which 6 Tolerance Units is Reached).....	130	27	98

pressure in the helix has certain shortcomings, still the fact that there is a certain increase in this pressure gives us the right to assume that, /84 in any case, it did not decrease to any significant amounts which could disturb the coordination of movements through a direct deterioration of

the central nervous system operation, caused by the deterioration of the blood supply. This means that all of the facts described by us should be basically attributed to distortion of peripheral information.

It can be thus concluded that, in the course of our investigations, we did not observe any side effects, which would hamper the correct solution of the basic problem.

Since an investigation of the dynamics for executing only one skill in increased fields of force might seem inadequate for completely proving the authenticity of our conclusions, we felt it was necessary to check them by other movements. For this purpose, we selected two more skills.

The first, differentiating presses by fingers of different hands on a hard support, differed from the skill investigated in the basic experiment, due to the fact that it was executed at a higher level of coordination.

The second, consisting of a proportional rotation of a half-bent (at the elbow) arm in the brachial joint, necessitated different movement kinematics.

The entire difference between the coordinational structure of the first control experiment (in some cases, it had an exploring character) and those of the basic experiment consisted only of the fact that the subject executed the presses not with one hand, but two. /85

In addition, with one of them (usually the left) he strived to press half as strongly as with the other. The evaluation of the quality with which the skill was executed and of the direction and the duration of overloads remained unchanged. However, much less time was spent on training of the subjects (about two hours).

In addition, no observations were conducted under an increasing overload. The number of subjects -- 3 people. Number of recordings -- two each.

Since, in this manner, the amount of collected material was inadequate for arriving at general mean values, we have listed (Table 4) the data on the index of force differentiation (the basic criterion for evaluating the qualitative execution of the skill and the magnitude of the pressing force) in all three subjects. In Figure 18, these data are illustrated graphically in the same relations as in Figure 15.

A comparison of the data, shown in Table 4, with the material obtained from an analysis of the main experiment, convinces us that even in a more complicated skill, with the use of two hands, similar rules can be discovered in the differentiation of force.

TABLE 4
DATA ON THE CONTROL OBSERVATIONS
(DIFFERENTIATION OF FORCES WITH TWO HANDS)

Subjects & Overloads	Index of Force Differen- tiation	Mean Value During the Overload Period			
		Magnitude of Presses, g		Mean Quadratic Deviation	
		Strong	Weak	Strong	Weak
D					
Background.....	0.85	4859	2623	<u>+ 617</u>	<u>+378</u>
4 Tol. Units...	0.62	5105	3148	<u>+1053</u>	<u>+579</u>
7 Tol. Units...	0.24	3994	2974	<u>+1252</u>	<u>+871</u>
V					
Background.....	0.84	4358	2362	<u>+ 456</u>	<u>+289</u>
3 Tol. Units...	0.46	2441	1664	<u>+ 291</u>	<u>+251</u>
5 Tol. Units...	0.34	3847	2864	<u>+ 396</u>	<u>+398</u>
R					
Background.....	0.77	4047	2878	<u>+ 326</u>	<u>+325</u>
4 Tol. Units...	0.38	4968	3599	<u>+ 399</u>	<u>+611</u>
7 Tol. Units...	0.20	5852	4864	<u>+ 533</u>	<u>+589</u>

Actually, in all cases we found an obvious deterioration of the index of force differentiation, which however, in the majority of observations underwent more noticeable changes. The same can be said about the fluctuation limits of the force magnitudes and their mean quadratic deviations. All of this, as can be seen, can be explained by the shorter training of the subjects, and, naturally, leads to a low K.

Finally, a graphic analysis of the data obtained from the first control experiment (Figure 18) also substantiates the main conclusions, since the corresponding dynamics of the index F satisfactorily approximate the lines representing the relation between the index and the logarithm of the field.

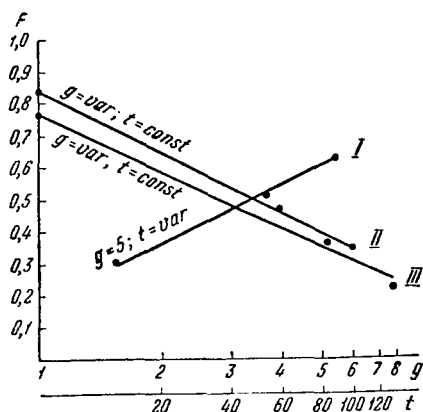


FIGURE 18

Relation Between Indices of Force Differentiation (F), Logarithms of Gravity Acceleration (g), and the Time Required to Execute Differentiated Presses with Fingers of Different Hands (t). Original. First Control Experiment. Data From Separate Observations.

I - Subject D; II - Subject-V; II - Subject-R; Other Notation is the Same as in Figure 15.

/86

The skill used in the second control experiment consisted of the subjects, repeatedly and with differentiation, shifting the arm, half-bent at the elbow joint, from the sagittal plane to the frontal by rotating the brachial joint. It was necessary for the forearm and the wrist to move in a horizontal plane. The skill consisted of a pair of movements. The first was moving the subject's arm within limits of 90° . In the second, he tried to keep the amplitude of the movement at one-half of the amplitude of the first. This regulation was the leading dynamic parameter of the coordinational structure of the particular movement. In each observation, during 100-200 seconds of overloads, up to 30 pairs of these skills were executed.

There was no visual control over the quality of the skill performance. In this way, if - in the main experiment, the control information, on which the activity of the checking organs of the external cycle regulating the particular skill was based, was transmitted almost entirely by the muscular receptors - then in this control experiment it often came from the articular and tendinous receptors. In other words, the selection of the skill for the second control experiment was predetermined by the attempt to check the basic conclusions by the movement, the kinematics. This meant that the control information would be different from that used in the basic observations.

At the same time, we must mention that the method employed in this control experiment created many difficulties for the subjects. If in the main experiment, they executed the skill with an immobile arm, the execution of movements selected for the control experiment called for considerable movements in space by a much heavier extremity. This, in the final analysis, resulted in our having to limit the accelerations, and not to conduct the observations in a field greater than 5 g.

In all other respects, the second control experiment was conducted under the same conditions as the main one. The quality with which the skill was executed was determined by the relation of the difference between the amplitude magnitude of the first and second movement to the amplitude magnitude of the second, and was evaluated by a similar coefficient F . The direction of the overloads and their duration were the same as those used in the main experiment.

The subjects underwent preliminary training, which ended when the skill was executed with a specific stability, and the index of force differentiation reached 0.89 in one subject and 0.95 in the other. It must be pointed out that in this case the skill was developed much faster (40-60 minutes in all of actual work) than in the preparation for the main experiment. This can be explained, evidently, by the already mentioned characteristics of the control information origin: /87 a skill based on the signals transmitted from the muscular, tendinous and articular receptors is mastered faster than the one whose signals come only from the muscular receptors (as occurs in the main experiment).

A total of three recordings were made, each during the entire execution of the skill, during rapidly - occurring stable overloads of 3 and 4 tolerance units. No observations were made during increased overloads.

The materials were processed under the conditions of the main experiment.

The second control experiment, as the first, substantiated the results of the main experiment. Regardless of the difference in the kinematics and the origin of the control information, the rules established from the main observations for the magnitude and the variability of forces agreed with the corresponding amplitude indices for the arm movements in the control experiment.

It thus follows that the index of differentiation for arm movements, corresponding to the index F of the main experiment, underwent similar changes during the execution of this skill in an increased field. (see Table 5 and Figure 19).

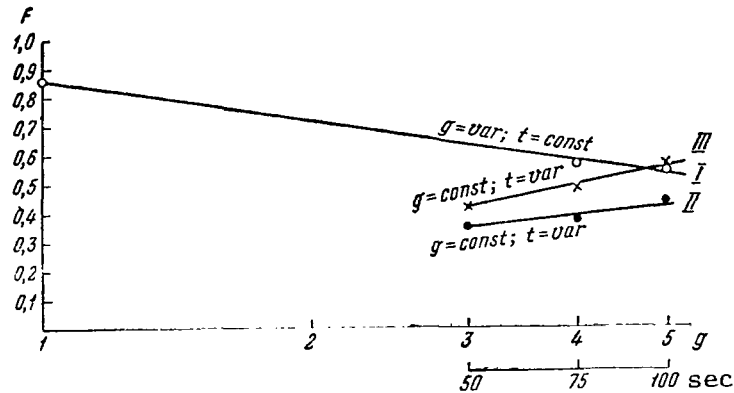


FIGURE 19

Relation Between the Indices of Force Differentiation of the Arm Movements (F), Logarithms of Gravity Acceleration (g), and the Time of Execution (t) for the Rotation of a Half-Bent Arm in the Brachial Joint Under Different Gravitational Fields. Second Control Experiment. Original.

I - Average Data During the Execution of the Skill in a Stable (for 100 Seconds) Field of 1, 4, 5 g.; II - Changes During the Last 50 Seconds of the Skill Performance in a Field of 4 g; III - The Same in a Field of 5 g. Data Based on Separate Experiments. The Rest of the Notation is the Same as in Figure 15.

From the information which appears in Table 5 and particularly /88 in Figure 19, it follows that the deterioration of the leading dynamic components of the particular movement, during its execution in an increased field of force, is basically subjected to that mathematical rule which was established during observations of faster skills. This can be seen from the fact that the relation between F and the logarithm of gravity acceleration in the corresponding field - in spite of the comparatively small parameters between the fields - satisfactorily approximates a straight line. The problem of re-establishing these components during numerous executions of the particular skill is somewhat more complex.

In the course of the main observations, the values of the leading dynamic skill components sharply deteriorated immediately after the start of the overloads, and then, slowly, but steadily, improved. At the same time, in a specific portion of observations, this proceeded in a logarithmic relation to the execution time of the skill (see

Table 2 and Figure 15). In the second control experiment, a somewhat different picture was observed. A noticeable deterioration of the leading dynamic skill components was not immediately apparent, but only 50-55 seconds after the skill was initiated under the conditions of overload (see Table 5). A slow improvement followed, with a return to the specific (not complete) norm.

TABLE 5
DATA ON THE SECOND CONTROL EXPERIMENT

Index	Without	During Overloads	
	Overloads (Background)	3 Tol. Units	4 Tol. Units
Differentiation of Arm Movements (F)			
Average of All Subjects for all Experiments	0.86	0.57	0.54
The Same in the Course of More Characteristic Observations			
Seconds From the Start of Overloads		In Subj. D	In Subj. P
From 1 to 29, Average	-	0.81	0.78
30 to 49, Average	-	0.48	0.46
50 to 60, Average	-	0.35	0.41
70 to 80, Average	-	0.38	0.47
90 to End of Overloads....	-	0.42	0.58

Figure 19 illustrates the improvement, which was observed in both subjects in separate, more characteristic tests. It can be readily /89 seen that its dynamics, in this period of execution, also is subject to the previously - established rule. As regards the increased resistance of this skill in the first period of overloads, as well as the comparatively fast rate at which it is mastered in the course of training, we are inclined to explain this by the more complete control information.

Thus, we can state that the control experiments substantiate the rules established during the main experiment.

In the course of the observations investigating the aftereffect of overloads in relation to movement coordination, we purposely asked the subjects not to stop the investigated skill for two minutes after the overload was removed.

An analysis of these observations made it possible for us to conclude that the after-effect does not have as pronounced an influence on the parameters of the leading dynamic components of the skill structure, as could be expected, considering the disturbances of movement coordination observed during increased force fields. In addition, during this time these indices not only returned to the norm but often were found to be considerably higher than when the skill was executed in a normal field.

This can be readily seen in Table 6.

TABLE 6

INFLUENCE OF THE AFTEREFFECT ON PARAMETERS OF LEADING DYNAMIC COMPONENTS IN PRESSING WITH A FINGER ON A HARD SUPPORT (INDEX F) ACCORDING TO DATA FOR INDIVIDUAL SUBJECTS

Subject	In Normal Field	After Stable Overload		After Increasing Overload Up To
		3 Tol. u.	7 Tol. u.	7 Tol. Units
Subject N	0.95	0.95	-	-
H	0.96	-	0.43	-
D	0.77	0.90	0.94	0.90

As it follows from Table 6, only in one case out of five, could the subject not re-establish coordination of the investigated skill in the two minute period, subsequent to the cessation of the overload. In all other cases, not only the restoration but also an improvement of the leading dynamic components of the particular skill, was observed.

The statements mentioned above indicate not only the nature of the aftereffect, but also the fact that the execution of movements under overload conditions can be one of the training methods for developing skill stability under increased gravitational fields.

CONCLUSIONS

The observations described in this chapter permit the following /90 conclusions.

1. Coordination of the individual's voluntary movements is impaired when the gravitational field is increased. Thus, the limits of impairment, insofar as the parameters of the leading dynamic components of movement can be determined and measured, depend on the state and training of the individual in this field, and are proportional to the logarithm of gravity acceleration.

2. Systematic performance of the changed motor skill in an increased gravitational field will result in restoration of movement coordination, i.e., in an approximation of the parameters of the coordination structure to their normal field values. This restoration will depend on the state and training of the individual in this field, and at separate periods will apparently be proportional to the logarithm of the time during which the movements are executed, provided that the field magnitude does not progressively increase and that the movement itself is performed frequently enough.

3. The proceeding unfolds possibilities for characterizing the muscular activity of individuals suffering the effects of a changed gravitational field, particularly in space flights.

4. The human being's capacity to restore movement coordination by systematically performing a skill under overload conditions can be the position from which to start working out the broad foundations for a cosmonaut's physical training, e. g., the training of motor habits needed to fulfill vital and labor functions in changed gravitational fields.

The problem of the subsequent state of coordination of the individual's movements when he performs them in a gravitational field increasing over a very long period requires further study.

CHAPTER III

COORDINATION OF THE VOLUNTARY MOVEMENTS OF MAN IN A ZERO GRAVITATIONAL FIELD (WEIGHTLESSNESS)

As pointed out in the introduction to the present work, the conclusions derived in studying the coordination of the individual's voluntary movements in an increased field were extrapolated to the zero field. This made it possible to prognose the possibility of maintaining movement coordination during the most prolonged phase of the cosmonaut's proposed flight - weightlessness. In this extrapolation, our starting point was that weightlessness is, in essence, a particular case of the gravitational field state. We postulated that the central organs controlling the individual's movements, and which are necessarily the first to react to field change, may readjust their activity independently of the direction in which the field changed (if, of course, we exclude the difficulties directly connected with moving the extremities in an increased field where they have taken on weight). In other words, one must assume that if the mechanisms regulating coordination of the individual's voluntary movements do not stand idly by when this coordination is impaired in increased fields, then under conditions of weightlessness - where the activity of the muscle periphery will in any case be no more complex than when overloaded - a similar phenomenon should be expected.

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This has been corroborated under conditions of temporary weightlessness and in flights of artificial manned earth satellites. This chapter gives a brief resumé of the data on observations accumulated under these conditions.

COORDINATION OF THE VOLUNTARY MOVEMENTS OF MAN UNDER CONDITIONS OF TEMPORARY WEIGHTLESSNESS

Temporary weightlessness lasting up to 40-50 sec may be produced in airplane flights on a Kepler curve. Many observations of an individual's voluntary movement coordination have been made under these conditions. Let us describe a number of them, which, in our opinion, are of the greatest importance.

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As pointed out in our work (Chkhaidze, 1962 b), M. A. Cherepakhin completely reproduced, in terms of weightlessness, our method of studying disturbances in the individual's voluntary motor coordination during gravitational field change.

In Figure 20 we have shown a sample recording of differentiated finger pressure on a solid support made by one of Cherepakhin's tes-

tees when passing into weightlessness, while in that state, and during the return to the effect of normal gravitational forces. As is readily ascertained from the figure, the greatest deterioration in the leading dynamic component of this skill may be seen in the first case, i.e., in the transition into weightlessness. By the end of his stay in the zero field (despite its brevity), the testee has to a certain degree regenerated his ability to differentiate pressures (the peaks, indicating the amount of pressure, have the requisite dimensionality). The subsequent transition to the normal field again impairs the coordination of this movement, but it is again soon restored.

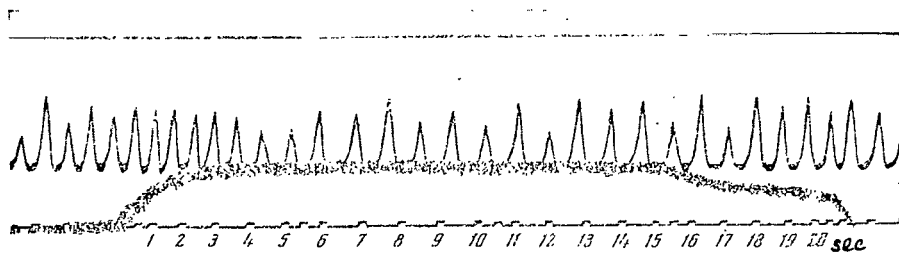


Figure 20.

Record of Differentiated Finger Pressure Against a Solid Support Performed Under Conditions of Complete Weightlessness (Using the Method and Conditions of in Figure 14) Upward Movement of Heavy Line Corresponds to Lack of Gravity. Experiments by M. A. Cherepakhin.)

Although the above now corroborates the validity of our extrapolations, let us turn to Table 7 which lists in 3-second time intervals the dynamics of coefficient F (which we have adopted as the index of pressure force differentiation) under conditions of brief weightlessness. These dynamics are derived from the mentioned recordings by Cherepakhin.

As Table 7 shows, the individual's ability to differentiate the finger pressures under discussion undergoes certain changes. At the first instants of weightlessness, the coefficient F , characterizing this ability, is very low (which was, however, to be expected). Then follows a slow but steady restoration, which, however, does not reach the norms (to all appearances, because the stay in weightlessness is too short). One fact must be pointed out here. If the quoted value of F is graphically expressed, with the duration of skill performance plotted on the abscissa axis in a logarithmic scale (Figure 21), no direct relation is

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established between the logarithm of the time required to perform the movement and the value of coefficient F. This coefficient is restored more rapidly than could be expected if compared to the course of this phenomenon in an increased field. The explanation for this may be provided by the easier conditions under which the skill is exercised. As is readily seen, this confirms the truth of the basic premise of the extrapolation mentioned above, and makes it possible to draw the conclusion that under conditions of weightlessness the individual's movement coordination should rapidly regenerate.

TABLE 7.
CHANGE IN COEFFICIENT F IN WEIGHTLESSNESS

	Horizontal Flight	Period of stay in weightlessness, sec					
		1-3	4-6	7-9	9-12	13-15	16-18
Mean value of coefficient of pressure force differentiation.	0,56	0,24	0,26	0,29	0,34	0,42	0,52

The problem of the individual's ability to sustain steady muscular force under conditions of short-term weightlessness (which is of particular importance for spaceship control) has been studied by Ye. M. Yuganov et al. (1962). These observations, which also in many ways confirm our extrapolations, can be reduced to the testees' trying to sustain a given force (400 g) with his unsupported finger on the lever of a dynamograph throughout the stay in a zero field. This is created during airplane flights along a Kepler curve.

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An analysis of the material amassed by this research has shown that if the testees maintained the prescribed force within fluctuation limits of ± 10 g during horizontal flight (i.e., under the normal effect of the gravitational field of the earth), then in the first seconds of the weightlessness period fluctuations in a 0-400 g range appeared. After many repetitions of this state, the capacity of the majority of the testees to sustain the force at a certain level, which is close to the given one, was gradually restored.

Similar results were earlier obtained in approximately identical investigations by V. S. Gurfinkel', P. K. Isakov, V. B. Malkin, et al. (1959), and by Ye. M. Yuganov, I. I. Kas'yan, N. N. Gurovskiy, V. I. Yazdovskiy, et al. (1961).

In his study of the effect of weightlessness on the motor

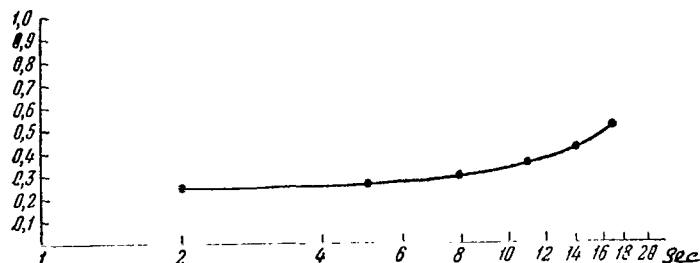


Figure 21.

Relation Between Differentiation Index of Finger Pressure Force (F) on Solid Support and Logarithm of Period of Stay in Zero Gravitational Field (Author's Processing of Experiments by M. A. Cherepakhin).

reactions of animals (the dogs Belka and Strelka) aboard an artificial earth satellite, B. A. Zhuravlev (1959) observed many similar phenomena, reminiscent of restoration of motor skill coordination after initial disturbance.

The works of Gerathewohl (1957) and Weitside (1961) should be singled out for mention from foreign research regarding human voluntary motor impairments which are possible during temporary weightlessness.

These investigators conducted observations of the individual's ability to estimate the leading dynamic components of a skill during weightlessness, by retaining the ability to hit a target with a certain object, e.g., a special pen (Gerathewohl's experiments, 1957) or merely the finger (Weitside's experiments, 1961).

The observational results showed that when the individual's vision is blocked, he tends, as a rule, to miss the point at which the object is aimed. The researchers have called this the oculo-gravitational effect. It is in our opinion a completely valid indication of disturbances in the operation of the checking mechanism of the inner cycle, which controls a given skill, due to an abrupt disturbance of the control information. A simple demonstration of this is the fact that Gerathewohl and Weitside are in agreement regarding the gradual restoration of the described skill (i.e., decrease in the oculo-gravitational effect) during the individual's repeated and /95

multiple sojourns under conditions of weightlessness¹. This agrees with the above-quoted data of Soviet scientists, and precisely indicates the reasons for the disturbances therein in a zero gravitational field, and the origin thereof, since - as we have repeatedly explained - the capacity for monotonic regeneration of the movement structure parameters is only inherent to the inner cycle, which regulates this movement.

To sum up the research on possible changes in the coordination of an individual's voluntary movements under conditions of short-term weightlessness, we must point out that all statements have led to basically the same conclusions: the initial deterioration of the skill pattern, which is caused by an abrupt change in the control information, must - as the adaptation of the individual in the zero gravitational field advances - be replaced by the restored parameter values of this pattern, and in the final analysis must lead to normal, or close to normal, movement coordination.

From all evidences, this restoration should not require much time. This conclusion has been corroborated in artificial manned satellite flights around the earth.

VOLUNTARY MOTOR COORDINATION OF MAN UNDER CONDITIONS OF PROLONGED WEIGHTLESSNESS.

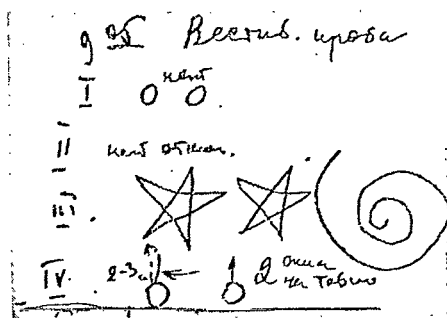
The literature at present lacks data on sufficiently extensive investigations of human voluntary movement coordination in prolonged weightlessness, e.g., data similar to those cited above. This deprives us of the opportunity of clarifying this matter in sufficient detail, but we can express justified considerations about it by taking into account a number of observations (and self-observations) of Soviet cosmonauts and American astronauts.

Yu. Gagarin, G. Titov, A. Nikolayev, P. Popovich, V. Bykovskiy, and V. Tereshkova agree in stating that they experienced no movement coordination disturbances under orbital flight conditions.

We can form a rather detailed opinion of this derived from data from G. Titov's report on his sensations during flight and quoted in the collection The First Space Flights by Man (Pervyye Kosmicheskiye Polety Cheloveka) (1962).

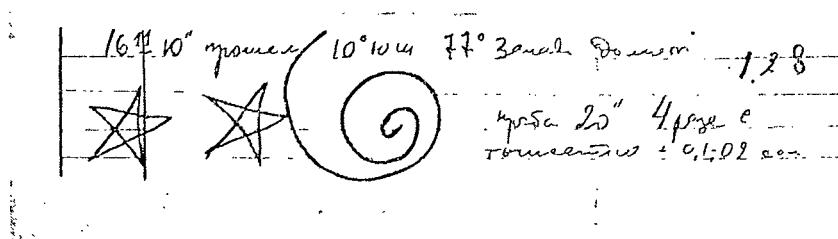
¹ Gerathewohl, for example, clearly states, "The testees adapted themselves to weightlessness in the first six experiments (our italics - L. Ch.). This is evident from the fact that the target is hit more accurately when the force of gravity decreases, than when it increases". (G. Aviat. Med., 28, No. 1, 1957, pp 7-12).

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Vestibular Tests and Handwriting of G. Titov on Earth
(While in the Mock-up of Spaceship Vostok)

"With closed eyes he easily and correctly drew five-pointed stars and two-and-a-half turn spiral, as he had under terrestrial conditions. On his own initiative, he several times in succession without any mistakes and with eyes closed touched the control levers and other objects at arm's length away. Movement coordination, according to G. Titov's statement, was not impaired throughout the flight."



Vestibular Tests and Handwriting of G. Titov in Space Flight.

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From the personal impressions of cosmonauts, it is fitting to quote an excerpt from the report of John Glenn to NASA in the U. S. A.

He writes: "In a sitting position at zero gravity, I felt more comfortable than in the same position on earth at 1 g, since I experienced no pressure. I very quickly adapted to the state of weightlessness (italics ours - L. Chkh.). I had no intention of taking any premature measures. I experienced no signs of coordination impairment (of movements - L. Chkh.), even in the first moments after separation (of capsule from carrier rocket - L. Chkh.). I unconsciously took advantage of the state of weightlessness, paying no attention, for example, to the objects floating in the capsule - cameras (moving picture - L. Chkh.), etc. I was otherwise occupied. This behavior of mine had not been thought out in advance, but was dictated by the situation itself, since another system (he is speaking of controlling the capsule - L. Chkh.) required my attention. The thought later occurred to me that my behavior then was just as natural as though the movie camera were lying on a table under 1 g conditions. I have been able to give only a poor illustration of how fast the human body adapts to conditions which are as foreign to it as weightlessness."

In summarizing what has been said, we must therefore note that even prolonged weightlessness causes no changes in the individual's movement coordination, which could result in a marked decrease in his ability to work, but to assert that he always maintains it under any circumstances would also be incorrect. From all appearances, we must assume that adequate and proper training should guarantee its restoration after a specific disturbance of a certain duration. However, the problem of the subsequent state of movement coordination during a very protracted sojourn (weeks or months) by a human being under conditions of weightlessness is still naturally unclear.

There is still a basis for assuming, however, that from all the findings the far greater danger in this regard lies in an individual's prolonged stay in increased gravitational fields. Here the weight increase of the extremities and the resultant drastic distortion of control information can lead to a more profound and extended impairment of the movement coordination for a person in such a field.

CONCLUSIONS

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The data cited in this chapter make it possible to draw the following conclusions:

1. An individual's stay in a zero gravitational field should involve no serious disorders of voluntary movement coordination if he has been adequately trained for this stay. A possible initial deterioration of the quality of the motor skills to be executed, which is caused by the transition to unusual conditions, is relatively rapidly replaced by the stable performance of the requisite dynamic components of the movement coordination pattern.

2. Proper training directed toward a goal may, however, minimize these disorders, and bring about the gradual restoration of movement coordination, even in increased (within a certain limit) gravitational fields.

CHAPTER IV

PRINCIPLES OF SPECIAL PHYSICAL TRAINING FOR MAN TO MAINTAIN VOLUNTARY MOVEMENT COORDINATION IN A CHANGED GRAVITATIONAL FIELD

We must now draw a number of practical conclusions from the material amassed. It can be readily seen that these conclusions must indicate methods for solving the principal problem - how to maintain or restore voluntary movement coordination of the individual who has found himself in a changed gravitational field.

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From the facts which we have ascertained, it is apparent that - regardless of the direction in which this field changed - there are two observable phenomena in the skill coordination pattern. First, the movement pattern is disturbed, and then it is gradually restored (if, of course, the field parameters do not change and the movement keeps on being performed). Both the first and the second phenomena take place in accord with certain laws.

Neither of these phenomena, as has been shown, is random, but they have an interrelationship and follow the general laws underlying the activity of the central organs which govern the human being's movements. In other words, if the basic information which provides the coordination pattern is sufficiently changed, this also entails disturbance of movement coordination itself. This deterioration of the skill parameters, however, cannot be maintained at the low initial level, and - if a movement is repeated frequently and the field strength does not change - then the skill pattern is gradually restored. This restoration is in turn, however, a consequence of what we have repeatedly pointed out. The checking mechanisms of the inner cycle controlling the movements do not remain indifferent to the skill pattern disturbances, and - if its operational program is sufficiently stable - immediately begin to readjust their own operation in order to approximate the value of the leading dynamic components of the skill pattern to the value which the altered field demands.

All this can be readily seen to be the result of a remarkable property of the human central nervous system - the capacity for plastic readjustment even under conditions which would appear to be unforeseen.

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This property of the central nervous system must also be used as the basis from which to solve the problem which has been posed.

This solution may be sought in different ways, e.g., finding and applying chemical, or perhaps biological, reagents capable of stimulating central nervous system activity in the requisite direction, or working out methods for the individual's physical training.

We shall not examine the first method in our work, since it seems to us that the second is more expedient at the present stage, more reliable, and less dangerous than the first.

The development of all the details in the cosmonaut's physical training - pre-flight and particularly in-flight - is a matter for the future, when enough experimental material, which has been tested and corroborated by experience, has been accumulated. However, if some of the features of modern sports training, which has recently achieved great successes, are taken into account, we may point out several general provisions of this training which ensue from the laws we have established. This is particularly easy to do, because the training of athletes is now very strictly organized and obeys repeatedly-tested rules. Based on these formulations, we shall try to plan ways of physically training individuals faced with activity in an altered gravitational field.

Before presenting this material, we must stipulate however, that all statements made below about the physical training of these individuals are applicable only to those who, after having been appropriately selected, prove to be capable of withstanding disturbances of the vestibular organs, particularly disturbances causing loss of spatial orientation. We need not mention that they must also be in generally perfect physical condition. We are dwelling on this point, only in order that the reader may not get the impression that future space flights are easy and accessible to anyone. No indeed, the cosmonaut's labor is heavy and requires not only long preparation, but also the capacity to withstand everything connected with it. No physical training will be effective unless the proper foundation has been established for it.

This position has also been generally adopted in modern athletic training, which is usually broken down into two parts:

- (a) the athlete's general physical training and
- (b) special training of his specific motor skills.

When the first part of this training is being carried out, the individual's basic physical qualities - strength, agility, speed, and stamina - are fully developed. The operation of all his most important internal systems - cardiovascular, respiratory, ex-

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cretory, etc. - are improved at the same time. This is achieved by selecting and performing a series of specific exercises which are aimed at perfecting the qualities indicated and the operation of the corresponding systems. Thus, the foundation is laid for what is to follow.

For the most part, the second part of the training, whose basic task is to develop the specific motor skills distinguishing a particular type of sport, is initiated when the body of the future athlete proves to be in some measure trained for it. Subsequently, after the initial skills have been mastered they are systematically perfected, but this cannot be separated from continuous training in new skills or (which is very important) from further general physical training. At different periods in the training, of course, the exercises comprising both these parts are chosen and proportioned out in different ways. However, that may be, they are always practiced in an inter-related fashion.

If the cosmonaut's training is approached from these standpoints, it may be subjected to the above rules. The cosmonaut cannot, in fact, avoid the general physical training of his body as a whole. Like any other athlete, he must develop his strength, agility, speed, and stamina, while his internal systems must undergo training, so that their operation will prove to be at its maximum level. This first part of training must therefore not be eliminated. The second part is imposed by virtue of its very nature - this is to perfect the skills which will represent voluntary movements for controlling the spaceship and for performing the daily functions of living and working. In other words, what for athletes is a skill technique in sports, will for the cosmonaut be his everyday action. Moreover, there will be no question here of performing these skills in the normal gravitational field of earth to which man is accustomed, but of training to perform them in a different, altered field. This comprises the essence of the cosmonaut's physical training.

Let us take a somewhat more detailed look at these questions.

1. General Physical Training of the Cosmonaut. It can be readily seen that the general physical training of the future cosmonaut must include exercises to improve his basic qualities and the operation of all the major systems of his body, on the one hand, and to help it resist overloads, on the other. While the first task is relatively easily solved by numerous and widely-known means (cross-country running, games, weight exercises), which need not be listed in all their details, the second task requires special equipment. The crux of the matter is that this portion of the general physical training must address itself to developing the resistance of the neuromuscular apparatus to lifting and landing

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acceleration, which cannot be done without simulating the respective conditions. This also refers, in particular, to training of the vestibular organs, which is of great importance in developing the special endurance of the cosmonaut. These devices are described in the literature (Pervyye Kosmicheskiye Polety Cheloveka [The First Space Flights by Man], 1962) and we shall therefore not repeat them. We would like only to mention here that not only can the special physical preparation of the cosmonaut be bridged, since - as shown below - the training must be done on certain similar devices or systems, but also a number of measures can be taken which will make the training more active.

However, this should not be misunderstood. All types of endurance development - for example, to overloads - should not be part of the special cosmonaut training. This is absolutely incorrect. The fact is that such training is to develop conditions for sustaining voluntary movement coordination in gravitational field changes. A passive set of exercises, which is applicable for developing endurance to overloads or for vestibular organ resistance, does not guarantee that movement coordination will be sustained, since it is known that this is developed only by training the motor skills themselves and can be replaced by nothing else.

2. Special Physical Training of the Cosmonaut. The theoretical foundations for the cosmonaut's special physical training follow from our discussion of the nature of movement coordination of the individual as a whole. As was demonstrated in the first chapter, the voluntary movement control of man, and apparently of the higher animals, may be regarded as the activity of two principal "cycles", one of which (the higher) controls the mental portion of movement (or skill), while the other controls the specific muscular synergies. Since the direct connection between the "cycles" is general, and the lower is subordinated to the higher, the control of certain specific synergies may in some cases (for example, in the examined changes of leading information - fluctuations in gravitational field strength) devolve on the higher (external) "cycle" to a certain extent. This will immediately impair movement coordination, since the magnitude and significance of the leading dynamic components of its pattern are provided by only the operation of the internal (lower) "cycle". For this purpose, this cycle has its own reverse connection and, in particular, its own checking organs which process the most important corrections on the course which the operational program of this "cycle" follows. These mechanisms act on information coming from the proprioceptors, while the external cycle bases the activity of its checking mechanisms on information coming from the external sense receptors. These receptors naturally, cannot provide the rapidly-flowing characteristics of muscular stresses, angular parameters of the section movements, and other data without which it is impossible to con-

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trol the specific synergies.

As we stressed at the beginning of this chapter, if the program in the internal cycle is stable enough, its control mechanisms, if trained for this, are capable of immediately adjusting their activity as soon as the conditions for performing a skill demand it. Consequently, the individual's special physical training, aimed at maintaining the coordination of his movements in a changed gravitational field, must include, first, formation and stabilization of the operational program of the internal cycle, which controls the specific muscular synergies comprising the coordination system of the respective vital and labor skills of the cosmonaut in a normal field. Secondly, it must include training the checking mechanisms of this cycle to adjust their activity in case the basic information - the gravitational field strength - changes. This change may take place in either direction - an increase or a decrease of field strength. The result of this adjustment is to return this regulatory function to the internal cycle; this also signifies that movement coordination has been restored.

This is all completely feasible. From the methodological aspect, there is naturally no difficulty in developing the major motor skills in a normal field. In such cases, it is customary to study and improve the skills for controlling a spacecraft; this naturally entails certain complexities, perhaps even large ones, but they are not significant from the point of view under consideration. We are not now speaking of the numerous, perhaps the majority, of movements associated with carrying out the functions of living, which are familiar to the cosmonaut from childhood. The second problem, the training of the internal cycle to adjust its activity, is far more complex. It is right here that the phenomena which we have described come to our aid.

In fact, as is evident from the material amassed, the change in field intensity in itself represents no danger, in the sense of an irreversible impairment of movement coordination. On the contrary, if a movement has been well mastered and the future cosmonaut is physically trained, this impairment fast fades away to nothing. Therefore, the corresponding mechanisms of the internal cycle are capable of this adjustment. It remains only to improve this capability by the required training methods. /104

This problem is solved in a relatively simple way if we proceed from the thesis, proved in the first chapter, that improvement of the performance quality of a motor skill consists in performing it many times under the appropriate conditions. In regard to the case which we are considering, these conditions may be only strengthened or weakened gravitational fields. Increased field strengths are

relatively easy to reproduce on the centrifuge, which is now widely known. Therefore, the training of the checking mechanisms of the internal movement control cycle for the necessary operational adjustment will have to consist of systematically performing all (or the principal) those movements which were previously worked out in a normal movement field in the centrifuge at different speeds. Thus not only will the given problem be solved, but at the same time the gap between developing bodily resistance to overloads and stability in movement coordination will be bridged over, as mentioned above.

The problem of training motor skills in a weakened field will have to be solved in some other way. It is a matter of common knowledge that it is practically impossible to generate such a field under terrestrial conditions. The brief weightless state achieved in an airplane flying along a Keplerian curve is clearly not long enough for any skills to be developed with confidence during this flight. Here, too, we must seek roundabout ways, one of which, it seems to us, may be again systematically to work out skills in heightened gravitational fields. In fact, as we showed in Chapter III, the checking mechanisms of the internal cycle can readjust their activity, regardless of the direction in which this field changes. Therefore, it should be a question of the ability of these mechanisms to readjust their activity in general, not in some one direction. Moreover, if this capability is developed for the difficult considerations of an increased field, it will not then be lost in the easier one - the lowered field. Hence, it follows that the cosmonaut's motor skill development (i.e., his special training) will have to be conducted in increased fields, and, from all appearances this should be sufficient for him to develop the ability to restore movement coordination in a lowered field, right down to weightlessness.

As for the dosage of the described centrifuge exercises, with respect to degree and duration of acceleration, it should be pointed out that the limits of training overloads must be determined by the feasibility of performing any certain movements under these conditions. At accelerations above 3 - 4 g it is known to be difficult, and often downright impossible, to move the body sections. This establishes the upper limit of the training accelerations for developing movement correlation in a changed gravitational field, although it may possibly be somewhat lower. The question of the duration of these training exercises for specific skills will be best solved experimentally. In all probability, at certain accelerations the optimum duration, as well as rate and rhythm, for executing movements will prove to vary for different exercises. /105

Such, in broad outline, are the principles underlying the physical training of individuals to sustain voluntary movement coordination during changes in the gravitational field. We refrain from making any concrete recommendations regarding, for example, the selection of

certain exercises and methods for mastering skills and perfecting them, since this is stipulated by the specific training conditions of definite individuals and does not enter into the problem we are reviewing.

In conclusion we deem it necessary to reduce all the considerations which we have expressed into a single brief table, which systematizes the data in accordance with existing rules for planning athletic training.

As Table 8 shows, all of the above statements make it possible to formulate in a well-proportioned manner the fundamentals of physical training for individuals faced with living under conditions of a changed gravitational field. Based on this table, individual charts and specific plans for preparing them may be prepared in the future.

After all the information given above, columns 1, 2, and 3 of Table 8 need no special explanation, since they systematize the theoretical considerations presented. We shall dwell only on the problems of periodizing training, principles of assigning exercises, and means of monitoring training quality and results.

It seems to us that the specific role of special physical training in the total complex of the cosmonaut's entire physical training must increase, as it develops and reach its maximum at the moment the ship is launched. General physical training, on the contrary, which plays the greatest role in the initial preparatory period¹, should gradually decrease in magnitude, but not be entirely /107 eliminated. This refers in particular to developing the body's resistance to lift-off and landing overloads, as well as to improving the activity of particular organs, (for example the vestibular organs).

Thus, in the main training period - i.e., when development of motor skills themselves begins - exercises from both training divisions are put into practice; to all appearances, this will enable several of them to be combined and make the training more active.

¹ In modern rules of planning athletic training, it is usually divided into several periods. The "preparatory period" is usually devoted to physical training; the "basic" - to mastering and improvement of the appropriate technical skills. A so-called "transition period" is simultaneously planned for the active recreation of the athlete after competition (not given in Table 8). This division is very conditional. It is difficult, in some cases, to periodize athletic training precisely.

TABLE 8

Approximate Planning of Individual's Physical Training for Maintaining His Voluntary Motor Coordination in Changed Gravitational Field.

Division of Training	Division of Tasks	Training Methods	Periodization	Amount	Control Over Training
1	2	3	4	5	6
General Physical Training	<u>General.</u> Development of strength, agility, speed, and stamina, operational improvement of cardiovascular, respiratory, and other systems.	Usual in general physical training (cross-country runs, games, exercises with weights etc.).	Mostly in Preparatory period. Only isolated exercises carried over into main period.	Individual, but with some increase in load toward end of training.	Completion of Norms. Medical check.
	<u>Particular.</u> Development of bodily resistance to lift-off and landing overloads. Improvement of vestibular organ operation.	Training on special equipment.	Same, but assigned somewhat more space in main period.	Same	Same
Special Physical Training	<u>General.</u> All major skills in working and living functions developed.	Mastery of movements associated with ship-control and living functions.	At end of preparatory and beginning of main period.	According to special conditions.	Total during mastery of skills.
	<u>Particular.</u> Developing resistance of these skills to changes in gravitational field.	Centrifuge training in mastered skills. May be combined with corresponding section of general training.	Mostly in basic period of training.	Individual, but with some increase in load toward end of training.	Depending on special norm (force differentiation index).

In our opinion, the elaboration and effectuation of this division of the cosmonaut's training should, on the whole, include the development of the most important motor skills, comprising the set of movements associated with performing the cosmonaut's living and working functions. A biochemical analysis of those which prove to be more or less complex for performance in increased gravitational fields, the development of methods on this basis for most rapidly mastering them, the study and rather significant stabilization of these skills by the cosmonauts in the normal gravitational field of the earth, and - finally and most important - training for these skills in heightened fields should also be included. This is specified in column 4 of Table 8.

We noted above that the proportionment of specific exercises was a purely individual matter, and depended on the condition and capacities of the individual trainee. We, nevertheless, believe that, in order to increase the training intensity gradually, despite all the individual elements which determine its choice, this proportionment should, as shown in column 5 of Table 8, increase somewhat toward the end of each period or division of training. This naturally does not refer to all types of exercises, but only to certain ones whose choice will depend on the training conditions.

The matter of checking the training results is resolved for special cosmonaut training much more simply than might have been expected. As was shown in Chapter II, the resistance of motor skills to a changed gravitational field is chiefly determined by the dimensionality of factor K which is included in the main equation. Therefore, its magnitude may represent adequate control over the course of training in motor skill stability at various accelerations. This may in practice be comparatively readily effected by using the individual's ability to differentiate finger pressure on a solid support as a test, under various conditions - for example, in a centrifuge, as was studied by us. This will, of course, require the development of the proper conditions for specifically evaluating the performance of this test, e. g., tables, etc. However, such a measure is entirely feasible and is of value, in that it will make it possible /108 to estimate the preparedness of the checking mechanisms of the internal movement control cycle and to resist gravitational field change. We have, therefore, entered this method for controlling the special training of the cosmonaut in column 6 of Table 8, together with other methods generally adapted for the remaining parts of his training.

In concluding this chapter, and with it our entire brief study, we feel it is necessary to point out that the cosmonaut's physical condition in flight is one of the most important factors in his success. It can be readily seen that if the computations of the flight trajectory parameters (radii and duration of revolution, etc.) are determined - among other things - the extent to which the prolonged accelerations in these revolutions enable the cosmonaut to withstand them - and, no less important, to perform the coordinated movements without which neither spaceship control nor intelligent life are possible - then both general training and, in

particular, specific physical training must develop the resistance of these skills to any changes in the gravitational field. It is natural that the greater this resistance proves to be, the greater will be the fluctuations in overload parameters which will be permissible in trajectory computations. In turn, this will permit savings both in flight time and fuel, for example. The entire significance of the question we have posed follows from this; for the present this question has been resolved in its most general outlines. The accumulation of appropriate experience will make it possible to approach more specific problems in a more detailed manner - in particular, the development of physical exercises to be performed by the cosmonaut during the flight itself, when protracted adynamia may create a number of significant factors negatively affecting his viability. The performance of these exercises will make it possible to restore the coordination of his motor skills, and, in general, to maintain his viability during weightlessness and during a prolonged rise in gravitational field strength. The whole set of exercises should, moreover, prepare the cosmonaut for the imminent changes in gravitational forces and acceleration when landing the spaceship on an unknown planet.

A general formulation the the forms and methods entailed in this training is, however, a matter for the future.

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